The
HOW AND WHY
Wonder Book of
BUILDING

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THE HOW AND WHY WONDER BOOK OF

BUILDING

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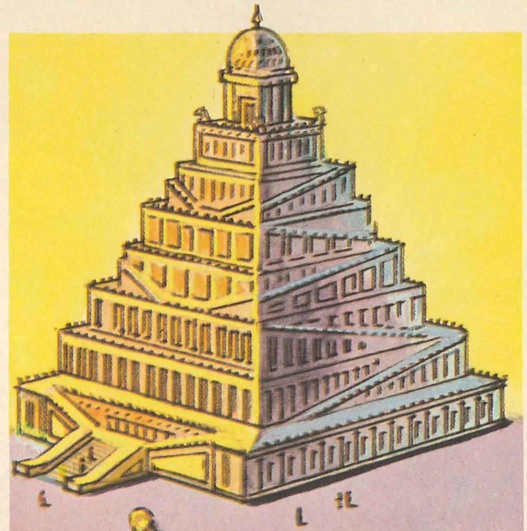
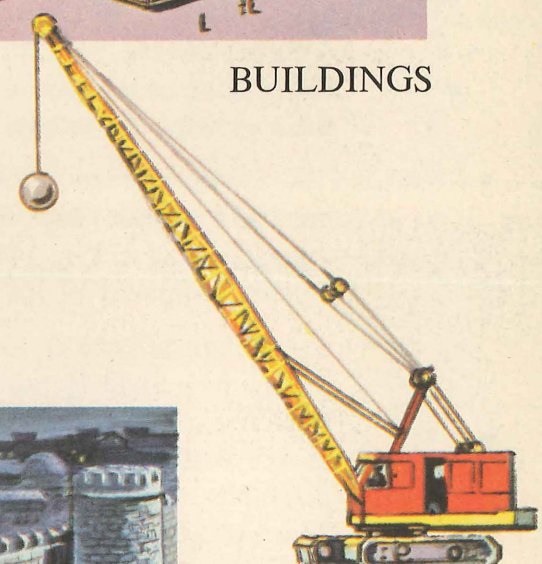


BUILDINGS



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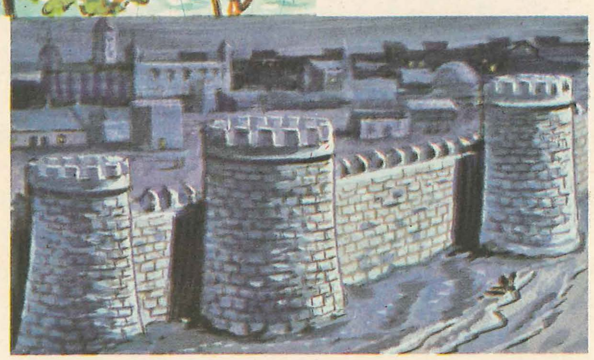

WALLS

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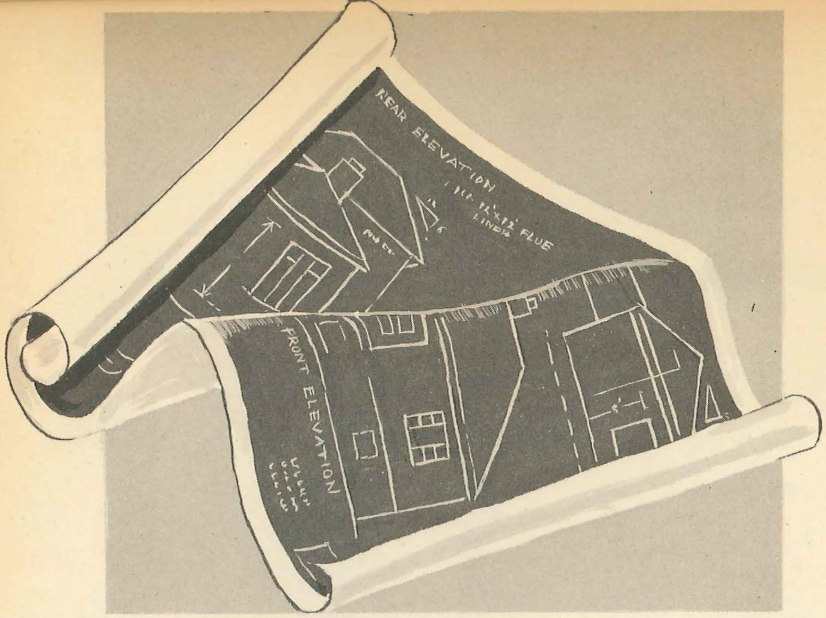

Introduction

This *How and Why Wonder Book of Building* can be read with equal enjoyment and profit from several different approaches. It can be read as *science.* We see how through the ages, men seek to discover principles of forces such as stresses and tensions and how they work in nature. Men test their growing knowledge as they build walls and bridges.

It can be read as *biography,* for we get a glimpse of the lives of great men and women who contributed to the world's engineering advances — "the Tiger of Ch'in," "Imhotep," the builder of a pyramid, and Colonel Roebling, builder of the Brooklyn Bridge, to mention a few.

It can be read as *history.* The Chinese Wall, the royal city of Knossos, the Empire State Building and the Brooklyn Bridge each, in its own way, influenced the lives of people and the development of nations. It can be read as *art.* Walls, buildings and bridges illustrate esthetic as well as engineering principles and can be viewed from the standpoint of creative and artistic expressions of men.

The liberal education of pupils requires an acquaintance with many fields of knowledge including science, history and art so well represented in this *How and Why Wonder Book of Building.* It is a fine addition to the home or school library for young readers.

Paul E. Blackwood

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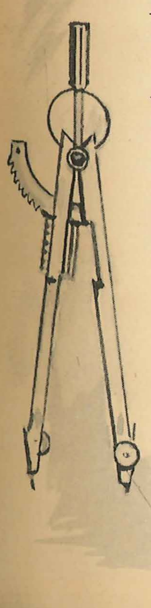
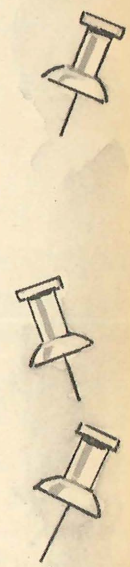
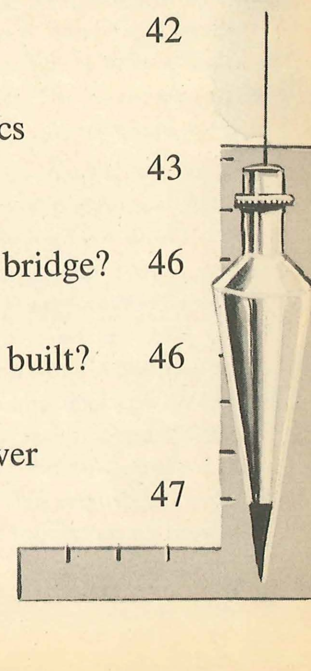
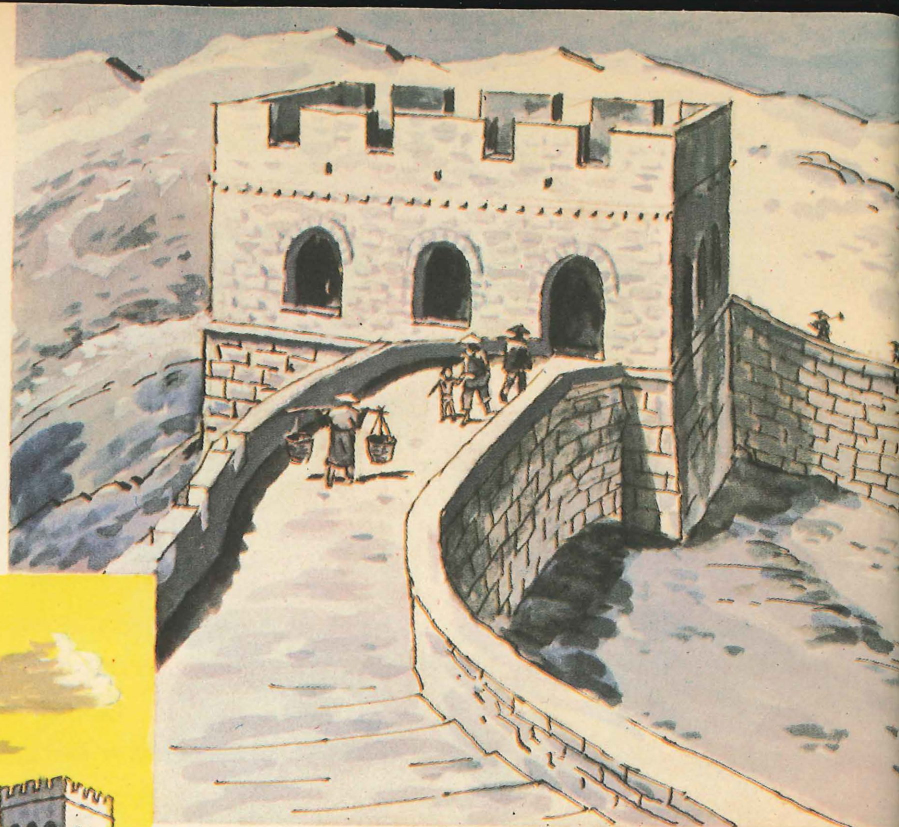


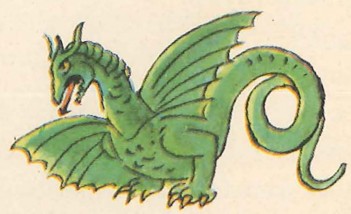




The roadway on top of the Great Wall between the protective fortifications was about 12 feet wide and paved.



In some sections where the slope of the mountains was especially steep, the road became stone steps which only a sure-footed man could travel.



BUILDING THE GREAT WALL

Finished about 200 B.C. at a cost in human labor beyond computation, the Great Wall of China, 2,000 miles of winding defensive structure, is a marvel of engineering that is difficult to surpass even with our modern equipments.

One of the legends told from generation to generation in China explains the reason for the many loops of the Wall: When the first bricks had just been put down it started to snow and the work was interrupted. The bricks became wet and soft. A tired giant dragon came along and rested against the wall, indenting it with his winding tail. When the workers came back after the snowfall stopped the dragon was gone, but they liked the design of the curving wall so much, that they went on building it the same way.

THE GREAT WALL OF CHINA

The news from the northwest border was bad, but the news from the Emperor's throne room was worse. The riders of the Hsiung-Nu Horde had again dashed out of the deserts of Mongolia into the peaceful farms of Kansu Province. Their horses had thundered through forty villages; their arrows and their bronze swords had left nine hundred men and women and children dead; and the fat herds of the patient, hardworking Chinese were being driven across the plains by the robber horsemen. That was the news from the border.

The Emperor of China was angry. That was the news from the throne room. The lords of the Emperor's Council were sent for, and went nervously to meet with their fierce ruler in the Crimson Room of the palace.

"Who will tell me how to kill these thieves?" asked the Emperor. The plump faces of the lords all turned to the Emperor's Chief Minister, Li-ssu, and the cunning eyes of Li-ssu stared calmly back at them.

One lord said in a low voice, "Your divine majesty will forgive my childish

Emperor Shih Huang Ti and the lords of his Council in the Crimson Room.

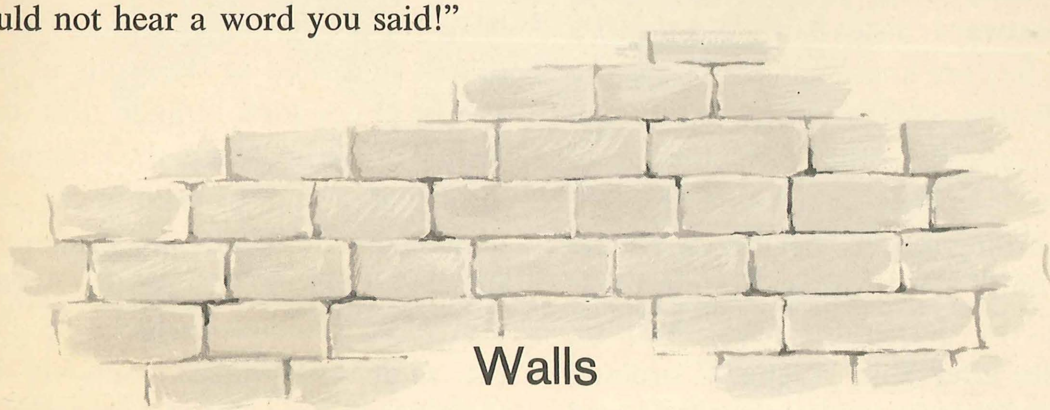
babbling, but if we cannot catch them, we cannot kill them. Would it not be better to arm the people of the northwest provinces? Then when the robbers return, our people can give battle to them? I only ask for the guidance of the divine Emperor on this point." Then Li-ssu spoke: "The divine Emperor has not forgotten the one hundred and eighty-two years of the Warring States of China." And the Emperor said fiercely, "No, I have not forgotten. Have the lords of this Council forgotten in one year? A year ago I was leader of the Ch'in, one of fifty peoples at war in this land. Now I am Shih Huang Ti, Emperor of all China, and now there will be no more Ch'in or Ch'i or Ch'u or Chou in China. There will only be China. No people will be armed in China to begin the wars of little peoples again."

Then Li-ssu spoke again: "The divine Emperor wishes his soldiers to win battles against these wild horsemen. Can any lord of this Council say how this is to be done?" Another lord said anxiously, "The divine Emperor will not be angry at a foolish old man, but a thousand horsemen can appear anywhere on two thousand miles of border. If the divine Emperor wishes to have a thousand soldiers to meet them at every mile of that border, his divine majesty might send an army of two million men." Then Li-ssu said, "The divine Emperor will not starve China to feed two million idle soldiers. The divine Emperor wishes to know where it is that a few soldiers on foot can win battles with many horsemen." Not one of the lords answered.

And the Emperor spoke: "I know where that is. It is in a fort. I shall make all China into a fort. A wall shall be built along the border. It shall be both thick and high, with many watchtowers and a few stout gates. Along the top of this wall my foot soldiers will patrol the two thousand miles of my northern border. And when the wild horsemen of the Hsiung-Nu come, my foot soldiers will defend the gates with their lives until *my* horsemen can ride up."

One lord was more daring than the others: "My ignorance is contemptible. Will his divine majesty tell us who is to build so great a wall?" The Emperor looked at the daring lord and said, "Why, *you* will build the wall, Wu Liang! Do not look so unhappy. You may have as many men as you please. And there are some old walls on the border. I will let you make them part of my great wall." The daring lord muttered, "Even so, it will take many lifetimes to build such a wall, your divine majesty." The Emperor replied in a friendly voice, "It will *not* take many lifetimes, Wu Liang." The lord Wu Liang said, "Then it will take many lives, your divine majesty." And the Emperor, friendlier than ever, said, "Yes, Wu Liang, it will take many lives. But if it takes more than twelve years, Wu Liang, *I* will take *your* life."

As the lords of the Council left the Crimson Room, Wu Liang murmured to the lord beside him, "The people are right when they call his majesty 'the Tiger of Ch'in.' He has all the mercy and generosity of a hungry tiger!" His friend hastily whispered back, "Alas, I am an old man and very deaf — I could not hear a word you said!"

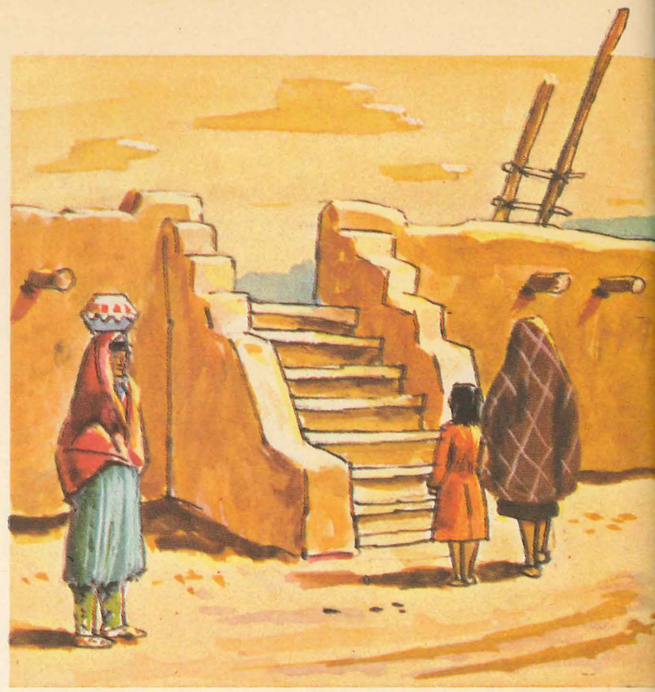


Walls

How did the building of the Great Wall influence world history?

Whether or not this story is true, it is true that the Emperor Shih Huang Ti made China a united country in 221 B.C. and that he has been known ever since as "the Tiger of Ch'in." And it is also true that the Great Wall of China, built at his command, can still be seen today, winding over the hills of northern China for 2,000 miles. And it is also true that the wall was completed in twelve years. And old historians record that it cost one million lives to build it — "a life for every stone," they say.

And some modern historians believe that because of the Great Wall, the dreaded riders of the Hsiung-Nu Horde

At left, long mounds of dirt and stones heaped up as high as possible (which is not very high) are the structures built by the so-called mound builders — Indian tribes of eastern and central North America. One does not know for sure who they were or why their civilization disappeared. One does not even know what the mounds were built for, although it is indicated that they were a kind of fortification and burial place.

At right, an adobe wall, built of mud with clay in it, has a better angle of repose, but the wall is not hard enough to give real protection in war.

turned away from China and began to ride westward instead. In our history books they are known as the Huns, the most feared of the barbarian tribes. They drove the other wild hordes of Asia and Europe before them, each tribe turning on its neighbors to the west, until the Roman Empire was overrun by desperate tribes. And six centuries after Shih Huang Ti ordered the building of a wall in the heart of China, Attila the Hun arrived at the gates of Rome. Engineering may change history in strange ways.

The strangest thing about the Great Wall of China is that it does not look strange at all. It would not have looked strange to Joshua, who ordered his soldiers to blow their trumpets loudly around the walls of Jericho while his engineers quietly dug away the earth underneath the stones. It would not have looked strange to Achilles, who fought and died at the walls of Troy. It would not look strange now to the people of Berlin, where the Communists have built a wall to keep in the people of East Berlin. Walls are similar at all times and places because there are certain basic principles which are always the same everywhere. Builders learn these principles from each other or from trying experiments with earth and stone and cement.

What is the angle of repose?

The first walls must have been just simple embankments — long mounds of dirt and stones heaped up as high as possible by the savages who wanted protection from the spears of their enemies. But

▲ A typical feature of Inca fortifications is seen in the fortress overlooking Cuzco, Peru, with walls built from huge blocks of dressed stone.

Your engineering ventures certainly have suffered while building your sand-castles. Now you know that it was the angle of repose which prevented you from building the walls higher, and why adding water to the sand improved the situation.

walls like that are not good protection; their sides are not steep enough and the enemy can charge over the wall.

If you have ever built sand-castles at the beach, or snow-forts in the winter time, you will have noticed something the engineers call the *angle of repose*. If you pile up clean dry sand, you will find that you cannot make the sides of the pile very steep. The sand slides down the sides until the pile is fat and low. No matter how carefully you pat the sand into place, there seems to be a certain slope that this particular sand can hold; the mound can be less steep than that, but not steeper. This slope is the angle of repose for that sand.

If you wet the sand, you change its angle of repose. Now you can make the pile steeper, because the water makes the grains of sand stick together a little. But as the sun dries out the pile of sand, you can watch little landslides starting, and soon the pile has flattened out again. If you could only find something that would keep the sand stuck together even when it was dry, you could make steep walls. Many kinds of earth contain things that will do this. Clay is one. Mud with enough clay in it will dry solid and you can build walls straight up and down with it. But these walls will not be hard enough to give much protection in time of war.

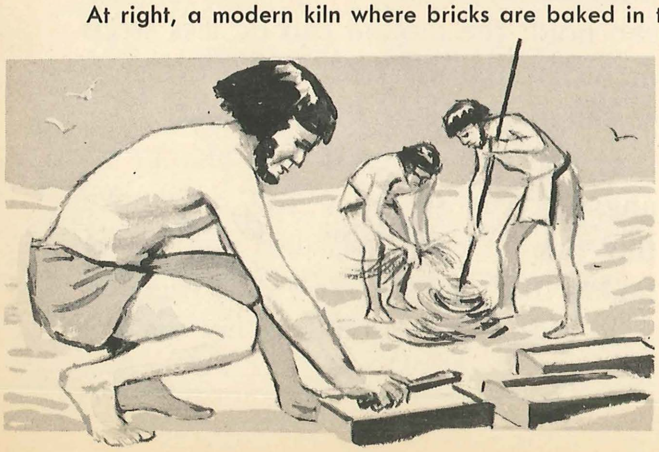
Rocks and stones are usually hard, but they are like giant grains of sand. If you pile them up just as you find them, without trying to fit their shapes together in any special way, you will find that they also have their angle of repose. You can do several things to make their angle of repose better. You can arrange the stones so that they fit together and hold each other in place. Still, it is not hard for anyone who wants to tear down your wall to pull a stone loose and bring the whole structure tumbling down. You can make the rocks stick together by putting clay or some other kind of cement or mortar between them. You can chip or chop at the rocks to make them flat on top and bottom and sides, so that they form blocks that fit closely together and do not roll off each other. This is called "dressing" the stone. You can shape the rocks *and* cement them together too, making a very strong kind of wall.

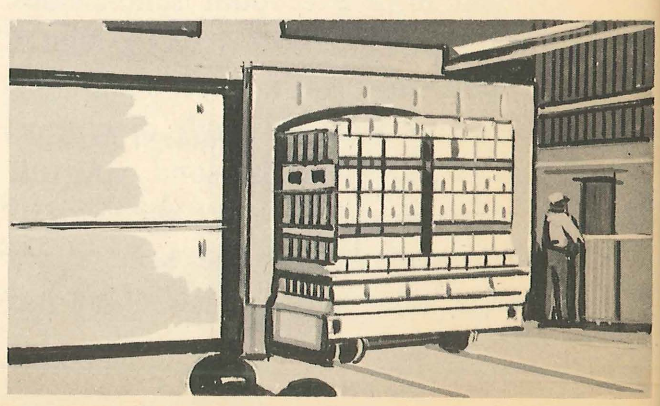
Obviously, it is not easy to shape stone into squared blocks. But thousands of years ago, men discovered that when certain kinds of mud and clay are baked in an oven, they become extremely hard and strong. By shaping mud and clay into blocks and baking these blocks in big ovens called "kilns," man could make bricks for building walls which would stand straight up.

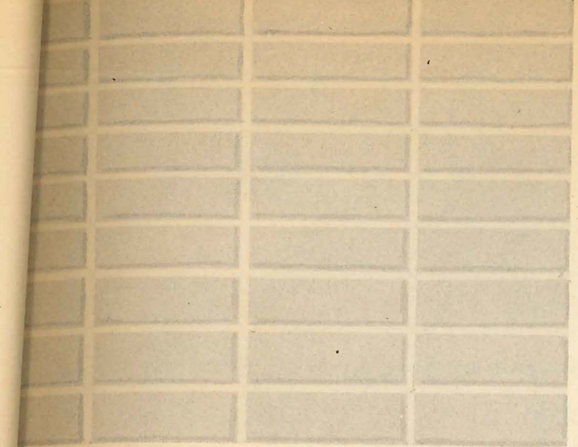
How are the bricks in a wall arranged?

You will notice that when bricks or squared stone blocks are arranged in a wall, they are almost always set in level rows, even though the ground may be sloping. The rows are supposed to be absolutely level so that there is no danger of sliding. Each level row is called a *course*. You will also notice that in most walls, each course is laid in such a way that the ends of the bricks or blocks in it are right above the middles of the bricks or blocks in the course below. The builders of the Great Wall of China did this and modern builders do it. If you have some light blocks or some sugar cubes handy you can do a simple experiment to see why. First put down

Sun-dried bricks in ancient times were made by strengthening the mud with plant fibers, and baking it in the sun. At right, a modern kiln where bricks are baked in temperatures of over 2,000 degrees.





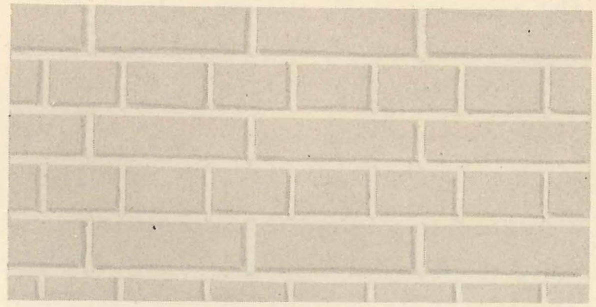


If the courses of brick form a pattern like the one above, you will notice that each brick is up against only four other bricks.

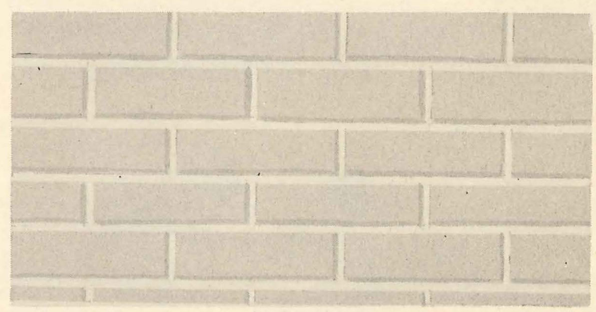
some "bricks" end to end in a straight row. Then lay a second course on top of it, with the ends of the "bricks" exactly lined up with the ends of the "bricks" below, and add a few more courses the same way. Now push gently with your finger against the wall. You will see how easy it is to topple a column of "bricks" laid one on top of the other. Now start your wall over again, lining up the ends of the "bricks" with the middles of the "bricks" below. Push gently, and you will see how the "bricks" grip each other a little bit and are harder to upset. They hold each other almost like the teeth of a zipper.

This is not just a trick that builders have discovered. It is a logical principle. If you consider the first way you built your experimental wall, you will see that each "brick" is up against four other "bricks," which help to hold it in place. If you study your second way, you will see that each "brick" is held in place by six other "bricks" instead of four.

There are many principles like this in wall-building. Some have to do with the wall itself, such as how thick you



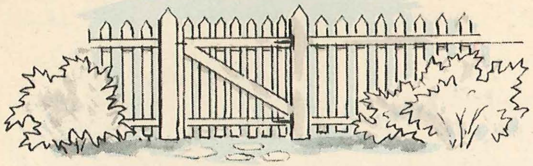
If the wall is more than one brick deep, often the bricks are laid in the way illustrated above. This gives them more support by having each brick in one course held in place by more bricks than in the illustration below, where each brick is held by six others. It also gives more support in depth.



should make it if it has to be a certain height. Some principles have to do with the "footing" of the wall, such as how to make sure that the earth beneath it will hold it up firmly. Some of the most important principles, strangely enough, have to do with holes in walls.

It is usually necessary to have a gate or door somewhere in a wall. If the wall is a low one, this is no problem. You just leave out a piece of the wall and hang a gate across the opening on hinges. But suppose the wall

How can weight be supported over an open space?



is a high wall and you only want an opening in the lower part of it. How do you keep the blocks or bricks above the opening from falling down? Engineers have solved this problem in three main ways: the *lintel,* the *corbelled arch,* and the *true arch.*

Let us work out these ways just the way a civil engineer does. Our problem here is the fact that gravity is pulling the bricks downward. We will call this downward force the *load.* We want to carry the load down to the ground *around* an opening.

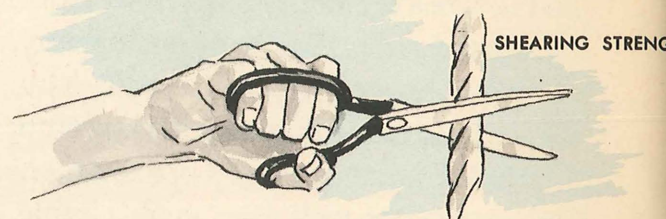
The more load we have to carry, the stronger our building materials will have to be. But there are three different kinds of strength: Suppose you put

COMPRESSIVE STRENGTH

a telephone book on the floor and stand on it. It will support the load, and it would easily carry the load of the heaviest person you know. Your weight is squeezing or "compressing" the telephone book. So we say the book has a lot of *compressive strength.* Now

TENSILE STRENGTH

suppose you tie a rope to a tree and swing from it by your hands. Your weight is pulling the rope, making it taut or "tense." So we say the rope has a certain *tensile strength.* Suppose while you were swinging someone took a pair of blunt, heavy scissors or garden shears and tried to snip the rope. But he found that unless he sawed the blades back and forth he couldn't cut it. We say the rope has *shearing strength.* A ma-

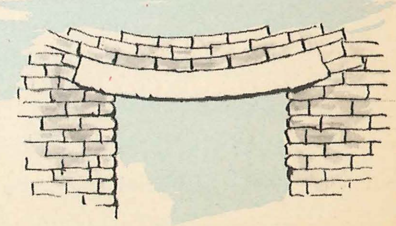


SHEARING STRENGTH

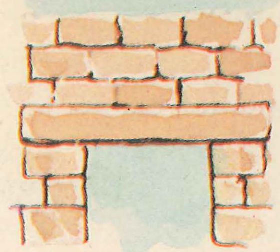
terial can have more of one kind of strength than another. A rope is good for pulling but not for pushing — it has tensile but not compressive strength. A pile of sand has some compressive strength but almost no tensile strength.

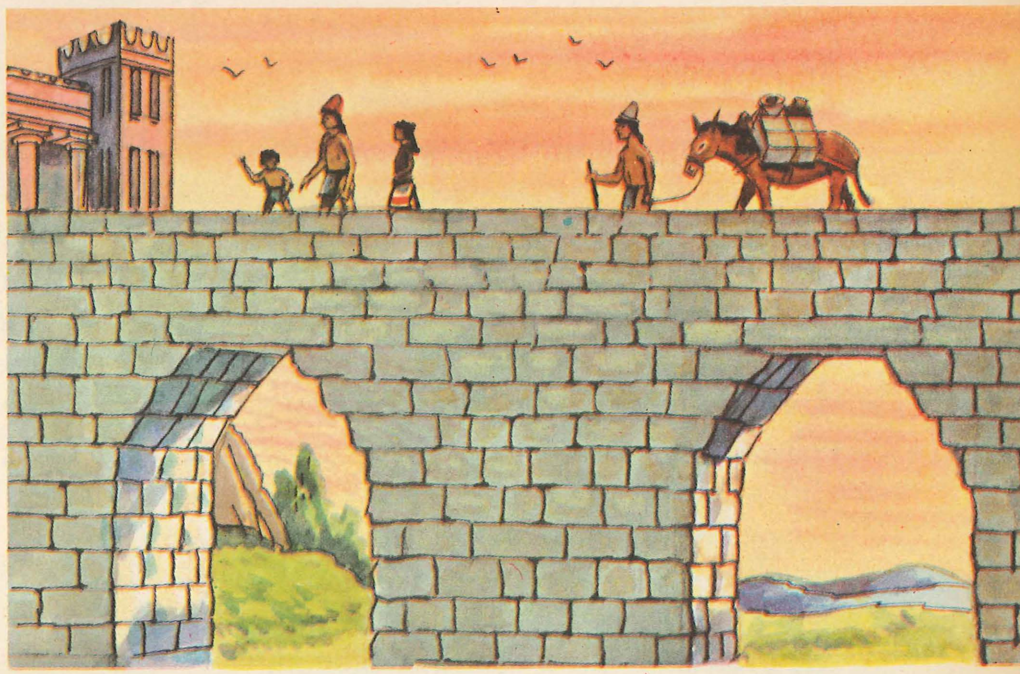
Now let us suppose we are going to build a brick wall 12 feet high with a door-opening in it 3 feet wide and 6 feet high. We lay our first course of bricks, leaving a 3-foot gap. We lay our second (leaving the gap), our third, our fourth, and so on, until the bricks are 6 feet high. We take a beam of wood about

LINTEL SHOWING INSUFFICIENT COMPRESSIVE STRENGTH

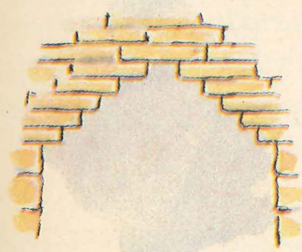


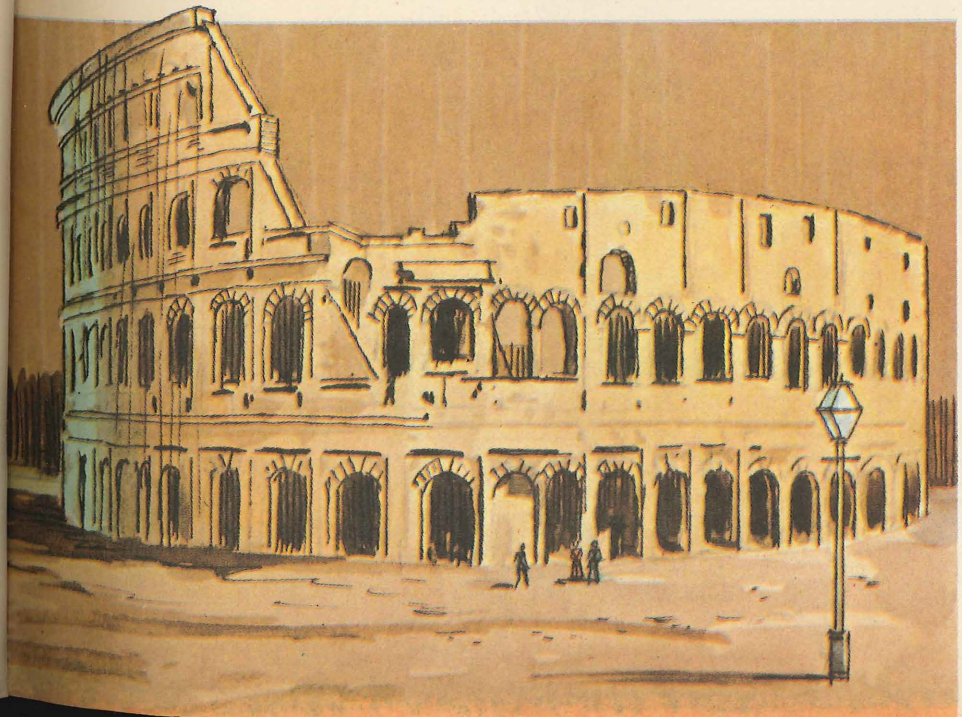
The Gate of the Lions at the entrance of Mycenae, a city in southern Greece, dates from 1200 B.C. and is based on the beam and lintel principle.



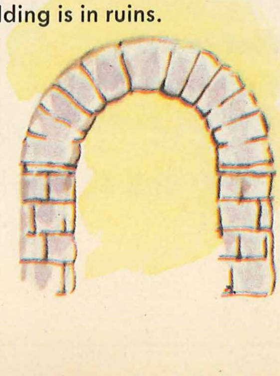


Corbelled arches on viaduct leading to the Palace of Knossos.





Many of the true arches in the outside wall of the Colosseum in Rome, built between 70 and 82 A.D., are still standing and impressive even if some of the building is in ruins.

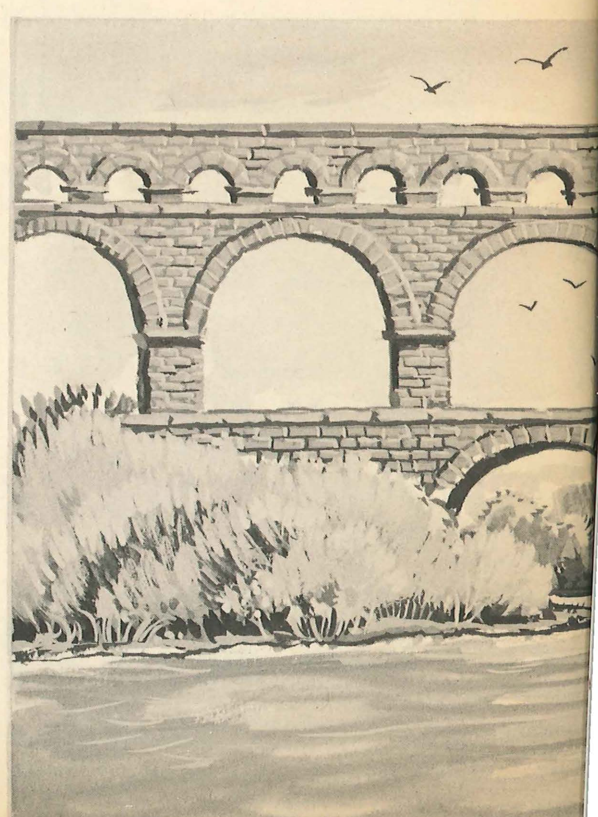


8 feet long and lay it across the top of the gap, with each end resting on the bricks. "Now," we say to ourselves, "we can lay our bricks on top of this cross-piece or lintel. The wooden beam will take the load of all the bricks on top of it and shift it to the bricks at the sides of the opening."

But let us see what really happens to that lintel. It begins to sag in the middle. Will it be strong enough? To answer that, we have to know which kind of strength we are talking about. If the wood does not have enough shearing strength, the ends of the beam will be pinched off. The underside of the beam is being stretched by the bending. Also, the upper part of the beam is actually being squeezed shorter by the bending, and you can test this with your telephone book. Simply hold the book so you are looking at the top or bottom edge of it, clamp your hands very tightly on the two nearest corners so that the corners stay squared up; and try to bend the book downward into a curve. The lower pages are stretched tight. The upper pages loop out loosely. This tells us that our wooden lintel must have both tensile and compressive strength. Luckily, wood has both. Unluckily, wood rots and burns. "Well, then," we say, "we'll make our lintel out of a stone block." But stone has rather poor tensile strength.

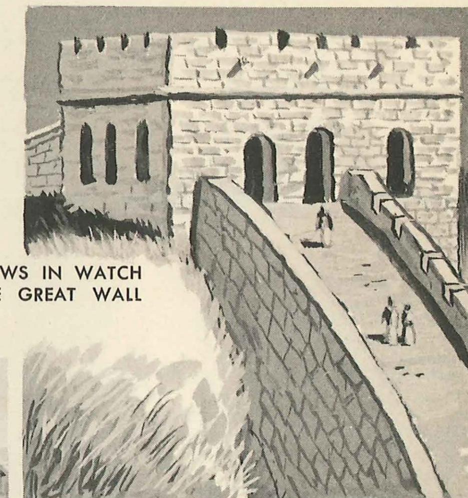
What is the advantage of the corbelled arch?

Is there some way we can carry this load by using only compressive strength and shearing strength? Yes, we can do it with the corbelled arch. Suppose we lay our bricks up to 6 feet, leaving the 3-foot gap. Then, instead of having the sides of the opening continue straight up, we let a brick stick out a little way on each side of the gap. We let the bricks in the next course stick out further, and the next still further, like an upside-down flight of stairs, so that the sides of the opening keep getting closer together. Eventually, they will join. "Wait a minute," we say, "won't the bricks that stick out over the opening tip over and fall down?" But when we look carefully at each brick that sticks out, we see that the end which sticks out cannot tip downward because this would mean its other end would have to tip upward, and the weight of the bricks above keeps that from happening. Each brick is like a little see-saw which is always weighted down on the side *away* from the opening. The builders of the tombs of the kings of Ur, in the Ancient Near East, used corbelling in 2500 B.C., and those arches are still standing.

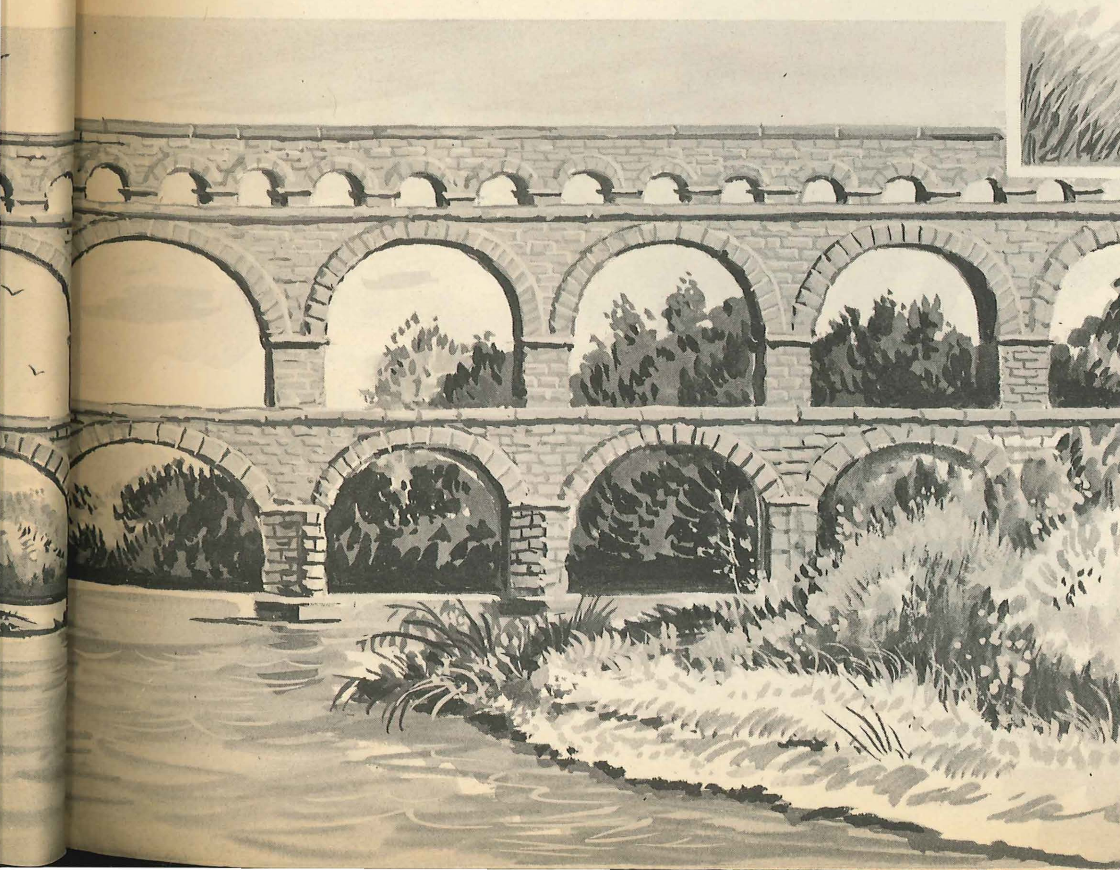


How is the true arch built?

Even after corbelled arches were invented, it took hundreds of years to invent the true arch, a really brilliant idea. Someone probably said to himself, "The lintel bends downward. I'll start with a lintel that is already bent upward, and that will take care of the sag." But there is much more to the idea than that. Suppose once again we lay our bricks up to 6 feet, leaving the 3-foot gap, and now suppose we dress some stones or bricks so that they are thicker at one end than the other. Now we put these stones one on the other with all the thick ends together. If we have enough of these stones and they are all the same shape, the pile will go up, curve over, and come down again in a perfect half-circle. If we stand one end of this half circle on the bricks on one side of the gap, and the other end on the other side, the stones will form an arch over the opening, and then we can lay our bricks around and over this arch. "Yes," we say, "but why don't the stones at the top of the arch simply slide down and fall?" Because they are like wedges. The top stone of the arch, which is called the *keystone,* tries to slide down but cannot do so without forcing apart the stones on each side of it. Its downward push is changed to a sidewise *thrust* against the stones next to it and these carry the thrust to the next stones, and so on down around the opening. The load is shifted to a thrust. The gates and the watchtower windows in the Great Wall of China are true arches, and they still stand as firm and round as they did when the Tiger of Ch'in turned back the raiders of the Hsiung-Nu twenty-two centuries ago.

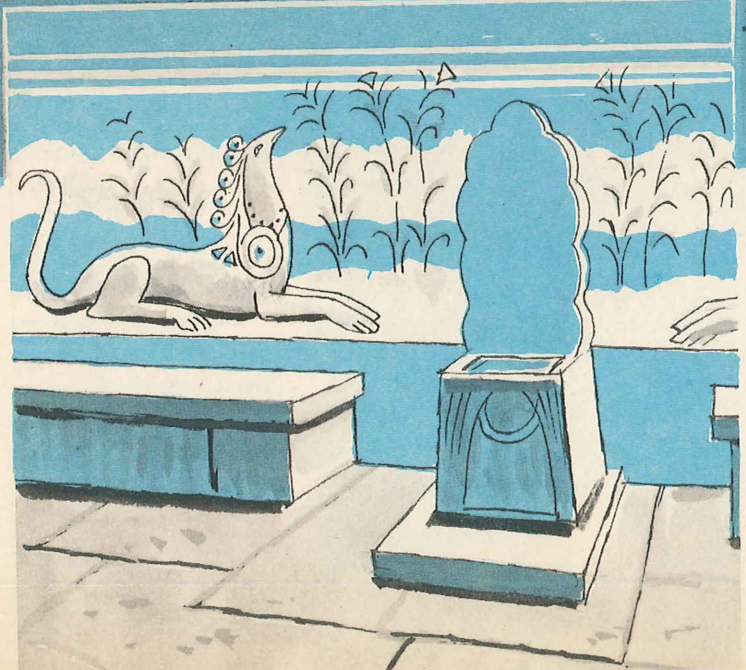


ARCHED WINDOWS IN WATCH TOWER OF THE GREAT WALL



Roman architects consistently used arches in the construction of the huge aqueducts. Built before the birth of Christ, they are still landmarks in Italy, France and Spain.

The Palace of Minos at Knossos was the center of the governmental power during the Golden Age of Crete, which began after 1700 B.C.



The alabaster throne of the king stands against a wall covered with frescos in the throne room of the palace.

The huge central courtyard of the palace was used for religious and secular festivities.

THE ROYAL CITY OF KNOSSOS

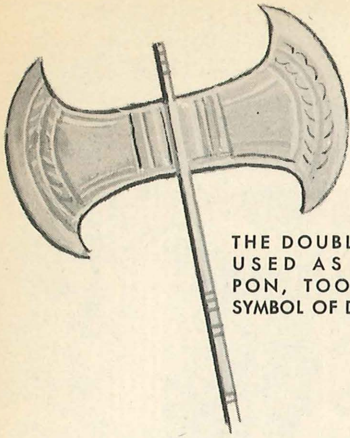
GOLDEN HEAD OF SACRED BULL

The boy shivered. Salt water dripped from the rags that had once been his tunic. His legs were too weak to hold him, so he sat down on a rock and lowered his head between his knees. After the dizziness passed, he raised his head and stared out at the sea. There was no trace of the ship, his ten comrades, the fierce captain, or the sudden storm that had wrecked them. The sea washed up on the pebbly coast in long, calm lines of waves. Poseidon, god of the seas, was no longer angry. The sun shone down from a calm sky. The sun-god Apollo did not seem to care that a good ship and eleven strong men had gone down.

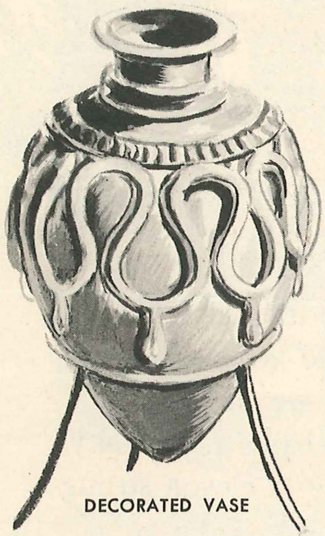
He heard a voice and looked around. Two men were watching him from a rocky ridge. They were dressed in cheerful colors in a strange, tight-waisted way that he recognized: they were men of Crete. He had seen Cretans before. Every sailor knew them, for they were the lords of the sea, and their navies swept proudly into every harbor in the world, and many kings on many islands were glad to pay tribute to the great King Minos of Crete.

But of course he had never been allowed to speak to any of the Cretans who came aboard the ship, for he was the youngest member of the crew — a shepherd boy from the hills of Greece who had run off to sea. He was still just a boy, and perhaps that was why the two haughty Cretans smiled as they beckoned to him. He stood up — a boy, alone in a strange land — and followed them.

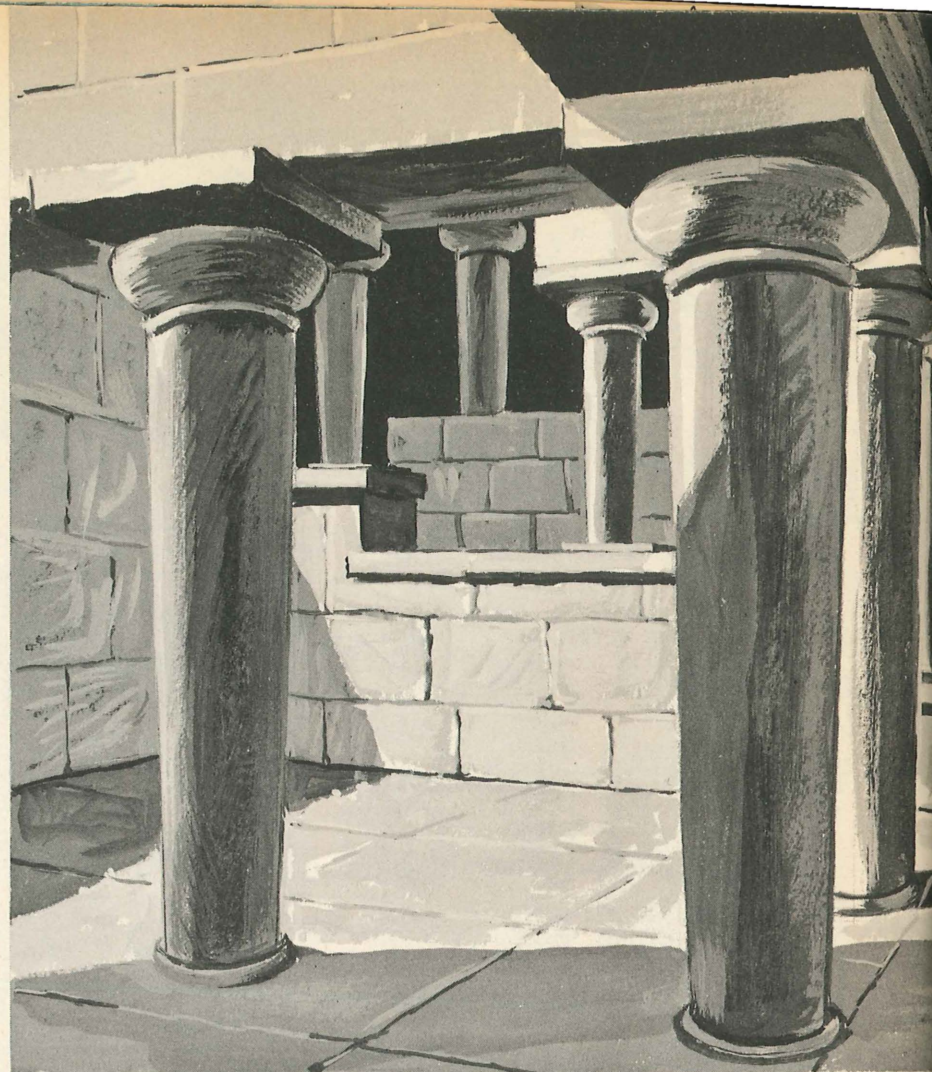
The next days and weeks were like a fever-dream. First, they traveled up into the hills, passing through cities with buildings in them bigger than any buildings he had ever seen. Some were of blocks of dried mud, others of square stones. He had seen tombs and temples built of stone before. But those



THE DOUBLE-AXE, USED AS WEAPON, TOOL AND SYMBOL OF DIVINITY



DECORATED VASE



Columns in the staircase in the palace at Knossos show the typical Minoan feature of narrowing toward the base. While the palace and most of the city were in ruins, archaeologists could reconstruct the features from pictures and reliefs on artifacts found on the site of the ancient civilization.

were like shepherds' huts compared to these! Yet, when he gaped in amazement at these structures, his companions smiled, as if to say, "These are nothing at all. You will see real buildings later." When they stayed overnight in these buildings, he could see that his friends must be the friends of some of the greatest lords of the world, for they slept in rich beds in rooms scented with spices. He himself was allowed to sleep among the servants and men-at-arms inside the big houses, lying comfortably on the floor in a robe they had given him. But he was so excited that he could hardly sleep.

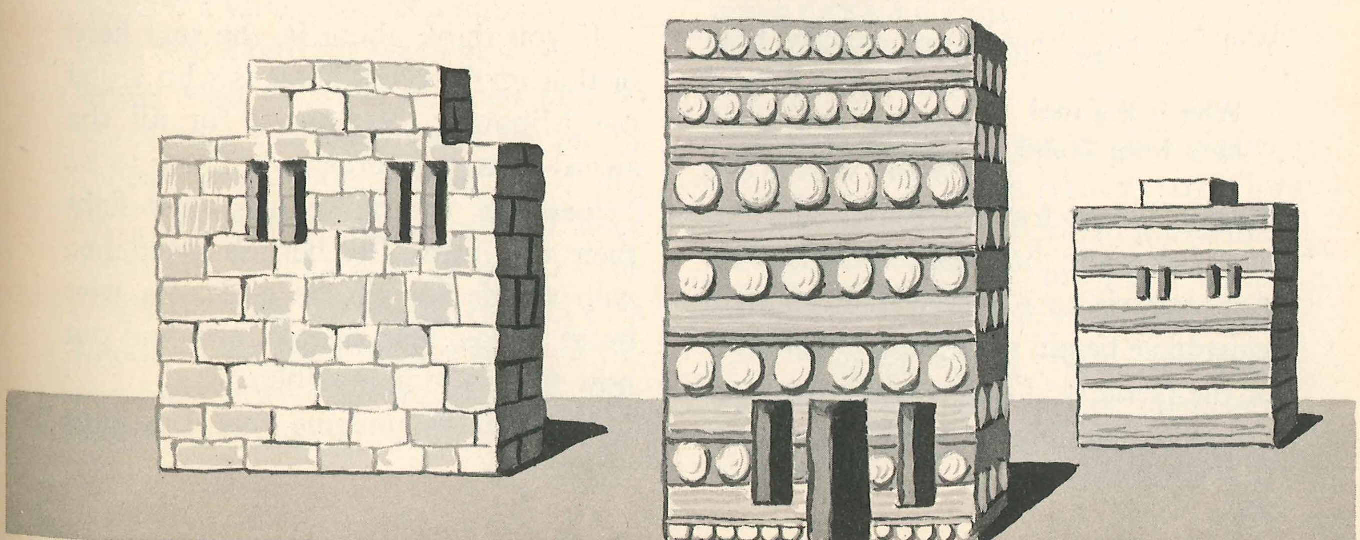
In the houses he noticed many statues of bulls, and sometimes he passed sacred gardens where there were live bulls, very clean and decorated with flowers. Cretans, he thought, must worship bulls. He also noticed, hung in places of honor in the houses, the kind of double-edged axe called the labrys that seemed to mean something special to the Cretans.

At last he came with his two lords to the royal city of Knossos and to the Palace of the great King. And there, over the doorway, was carved the image of the labrys, the axe. And the other buildings that had amazed him were like shepherds' huts compared to the Palace. Surely the gods themselves did not live in splendor like this! The walls were of stone blocks, so big that he knew a whole ship's crew could not have lifted one of them. How could they have been set one on top of the other? The man who did that must have been a magician, wiser than the gods! The roofs were laid across huge timbers supported by fat round pillars of stone. There were immense staircases. And rooms that could have held four homes like the hut of sticks and clay where he and his whole family had lived — rooms piled one on top of the other, more rooms than he knew how to count. There were rooms with baths in them! It would have taken twenty servants to carry in the jars of water for those wonderful great bowls where the lords of the world sat and washed. No servants carried the water; it flowed in through tubes made of pottery: cold water through some, hot water through others! Hundreds of rooms with endless passageways between the rooms. Even a wise man could get lost in this Palace that was bigger than a whole city.

In the heart of this frightening and wonderful place was a great courtyard paved with stone, and in this court was a fierce white bull — the king of bulls, a holy bull! "Perhaps I am not going to be a slave," the boy thought to himself. "Perhaps I am to be sacrificed to the bull-god." He had heard of such things.

But it turned out that he was a slave after all. His masters amused at his amazement, kept him at Knossos for a few days. Once he saw the mighty King Minos in the distance. Once he saw the Princess, and he thought her the most beautiful of all the beautiful Cretan women. And once he saw his masters talking with a man called Daedalus, who was the King's Chief Builder. (Daedalus looked like an ordinary man, but if he were builder of the Palace, he was not ordinary!) Then the slave boy was sent off to a farm in the hills, then sold to a ship-builder, then traded to a merchant. He ran away from the merchant

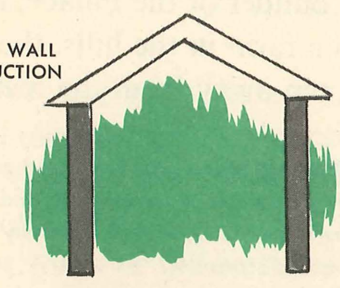
Houses in Knossos did not show the spaciousness of the palace, but they were very advanced compared to the rest of the contemporary European world. A reconstruction was made from plaques and pictures showing two-story buildings with a raised top, flat roofs, windows in pairs, some with carefully squared masonry walls, some with horizontal wooden beams for stability and decoration.



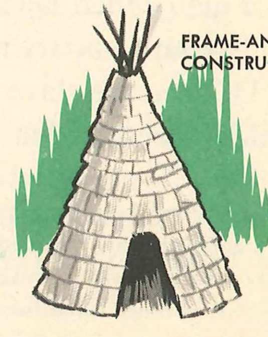
and after many adventures — but none of them like the visit to Knossos — he found his way back to the hills of Greece.

There, among his own people, he was regarded as a terrible liar. Whenever he told about the vast Palace where a wise man could get lost, about the fierce bull, about the mighty King and the fair Princess and the great Chief Builder, people laughed. But it was a good story, and people told it to their friends, improving it a little, and it got mixed up with some other exciting tales.

The story went from ear to ear for hundreds of years, and thousands of years. Of course, as the Greeks learned to put up big buildings of their own, they were less impressed by Knossos. The Palace where a wise man could get lost was changed in the story to a vast maze called the Labyrinth — after the labrys sign of the double-axe that the shipwrecked shepherd had described. The fierce bull was changed to a monster, half man and half bull, who ate boys and girls. A handsome hero was added to kill the monster, and the fair Princess naturally had to fall in love with him and get him out of the maze. For this she needed the help of the Chief Builder, of course, and the King was naturally furious. He imprisoned the Chief Builder in his own Labyrinth; but it seemed only reasonable that a man who could build a Labyrinth could do other marvelous things, such as fly. So the Builder built wings like an eagle's and flew to freedom. And that was perhaps the beginning of the myth of the Labyrinth, Daedalus, the Minotaur, Theseus, and Ariadne. We still learn it in school, but we probably do not realize that it is the story of how people who know about engineering appear to people who do not know engineering.



Buildings



Who is the real hero from Crete?

Well, perhaps this is not exactly how the myths got started. But since 1894, when Sir Arthur Evans found the buried ruins of Knossos and the Palace of the Double Axe, experts have agreed that the myth must have begun with the astonishment of the primitive Greeks when they saw the great buildings of Crete.

If you think about it, the real hero of that myth is not Theseus who killed the Minotaur. He stands for all the sword-swinging heroes who have to be helped out of the scrapes they fight their way into. The hero is Daedalus, who stands for all the engineers who build things, help people, and find out how to do the impossible.

Now let us imagine that Daedalus

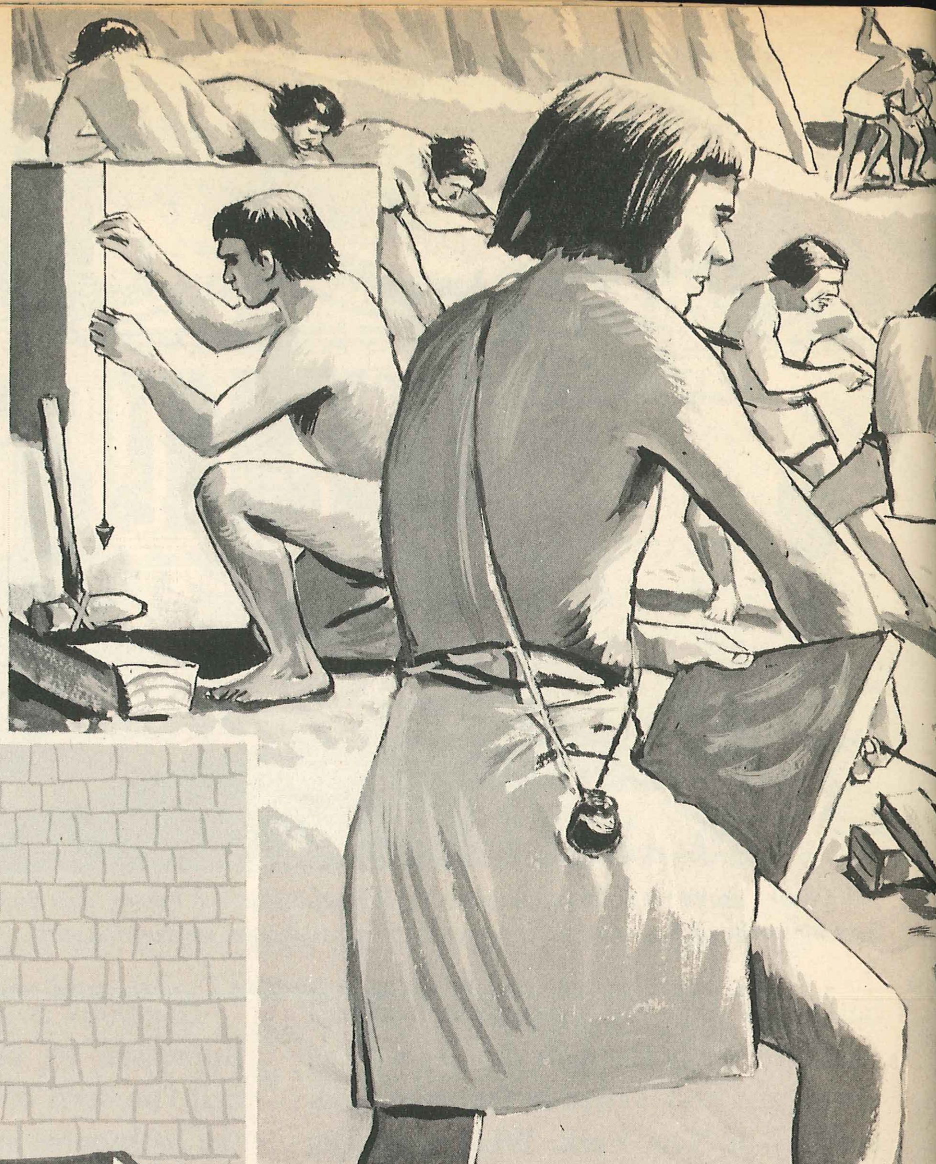
The Greeks learned well. Even today's ruins of the Acropolis of Athens, built during the Golden Age of Greece (late 5th century B.C.), command respect for their beauty and engineering skill.

had really done the impossible, and had managed to fly through time as well as space, and had landed in the great modern city of New York. What would he think? How would he feel, as he leaned back to look up at the Empire State building thrusting nearly a quarter of a mile into the air — like fifty great Palaces piled one on top of the other? How would he feel as he was pulled upwards in one of its 69 elevators at a speed of a thousand feet a minute? And what would he think when he saw Lever House with its walls of glass and its whole huge bulk held up in the air by a few spindly pillars? He, Daedalus, the Chief Builder in that great Palace where the Greeks learned part of the civilization that the whole world in turn learned from them, would feel just the way the shipwrecked shepherd boy felt looking at Knossos.

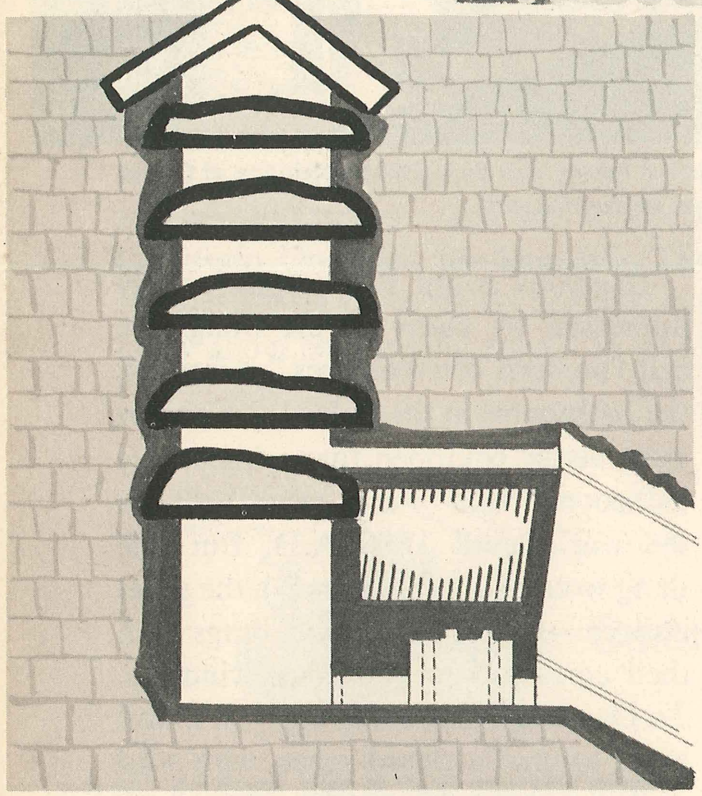
Daedalus might not be particularly impressed by many of the things we call "modern conveniences." After all, the bathrooms in the Palace at Knossos were better equipped than almost any bathrooms that were ever built in the world until 1800 A.D. But one thing would certainly astonish the great builder — our slim, tall buildings with their acres and acres of glass windows. To Daedalus, a building was just a wall going around a closed space, with a lid on top to keep the weather out.

What are the two types of wall construction?

For thousands of years, the master builders of the world followed that same plan when they designed palaces, temples, tombs, forts, stadiums, and every kind of grand or important building. This kind of construction is



Craftsmen cut and dressed the tremendous blocks of stone used for the building of the Royal Egyptian pyramid-burial places. Their construction is based on the post-and-lintel and bearing-wall construction principle. The huts of the workmen in the background are frame-and-skin construction.



Cutaway view of one of the Royal tombs, showing the construction schematically.

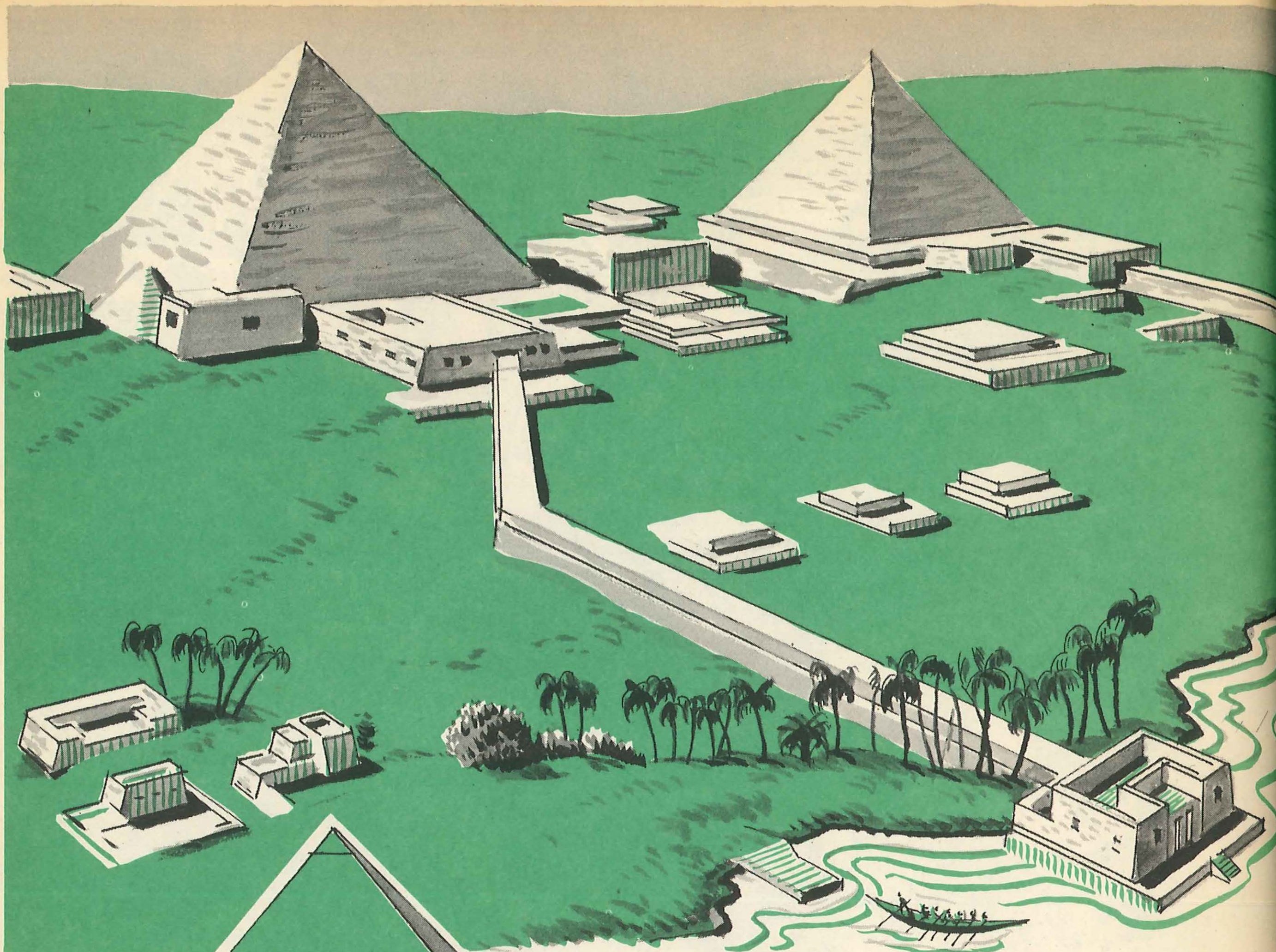
called *bearing-wall construction,* because the walls bear the whole load. They carry the weight of the roof and the floors and the furniture and the people and everything else. During the same thousands of years, most of the common people lived in huts and teepees and shacks and houses that used an entirely different principle, called *frame-and-skin construction.* In this kind of structure, the load is carried by a framework or skeleton, usually made of wood, while the walls and roof are a protective "skin" attached to the framework. Among many Indian tribes, for instance, the skin is actually made of the skins of animals. Among African tribesmen, it may be made of grass. Among American farmers, it is usually made of thin wooden clapboards and shingles.

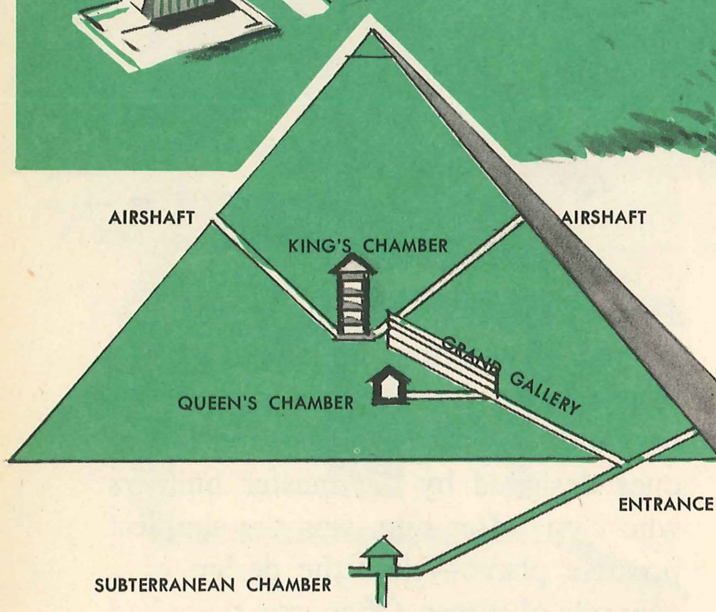
Why were all the structures that were built in honor of gods and Kings constructed one way, while all the structures that were built for ordinary people to live in were constructed another way?

Simply because bearing-wall construction uses stone, and stone lasts. Frame-and-skin construction uses materials that do not last but do not have to be hacked out of the earth by slaves, dressed by slaves, and hauled into place by hundreds of slaves.

What was the basic engineering principle of the Egyptian pyramids?

In ancient Egypt, the first builder to use dressed stone was Imhotep, "chief of all the works of the king" in the reign of Zoser. In 2980 B.C. he built a huge tomb for his royal master, in the shape of a pyramid as high as a modern 18-story building. For this he was considered so wise that he later was worshipped as a god. Yet the plan of his pyramid, and of the bigger and bigger ones designed by the master builders who came after him, was the simplest possible plan — just the design of a neat pile of stones. Of course, there had to be tunnels and burial-rooms inside the pyramids. The method used for supporting the immense load of the stones above these open spaces was also the simplest possible one — the lintel method. The lintels of the King's chamber in the Great Pyramid of Cheops are made of blocks of granite weighing 55 tons each.



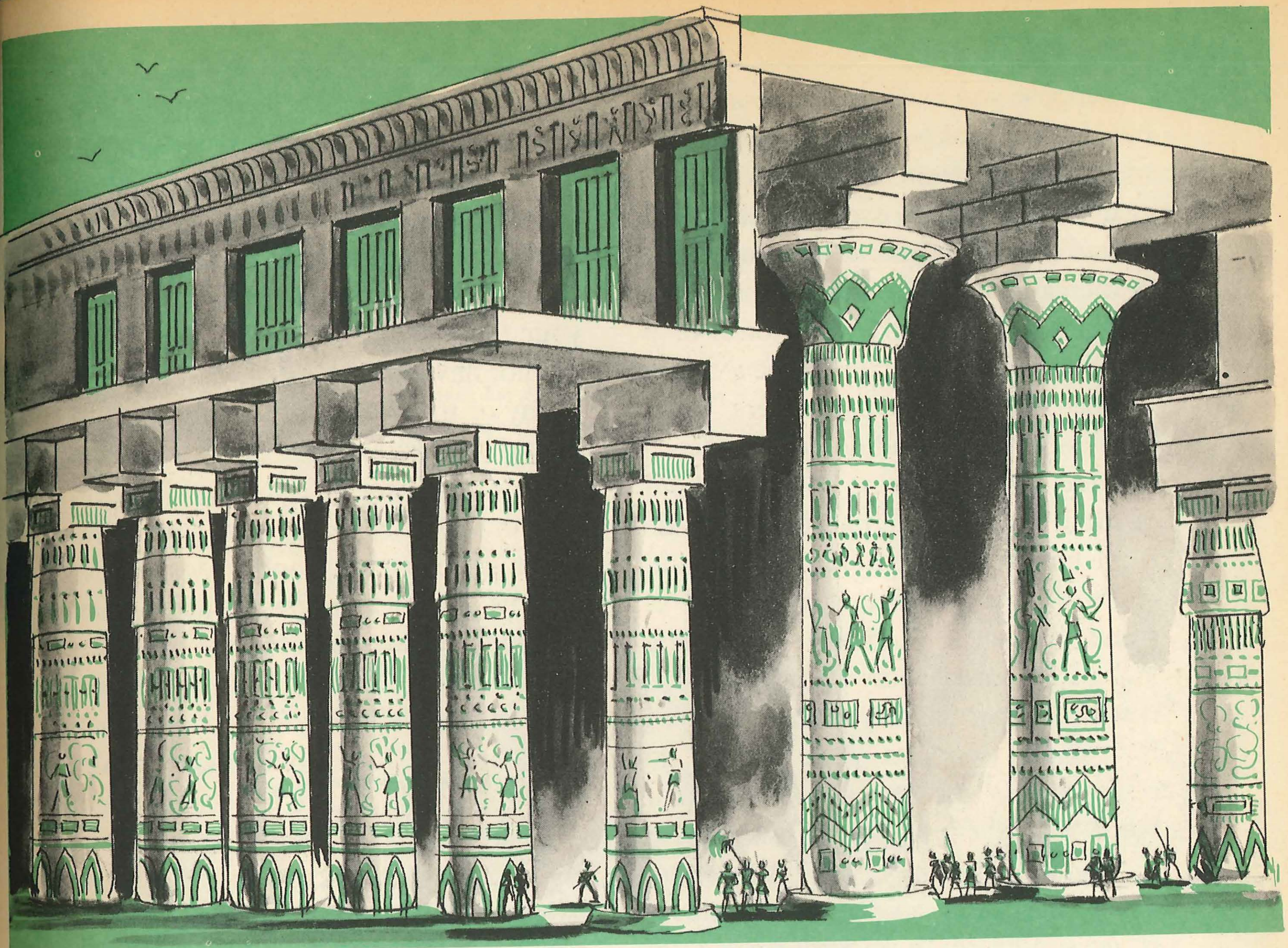


The pyramids as they might have looked in 250 B.C., and, at left, a cutaway view of the Pyramid of Cheops.

The temple at Karnak in Egypt was built, bit by bit, over thousands of years. Its floor space is larger than that of St. Peter's Church in Rome, the largest church in the world, *and* the great cathedral at Milan, *and* the cathedral of Notre Dame in Paris, all together. Yet it was built simply by laying tremendous lintels across the tops of columns made of huge stacks of stone blocks. Even the Palace at Knossos used the lintel method for its windows, doors, ceilings, and roofs. Roofs were not much of a problem to Daedalus, because usually the only load a roof had to carry was its own weight, so the lintel method worked well. The lintels or "beams" could be made of long pieces of timber with boards and clay or pieces of slate laid across them.

What is the function of vaults and domes?

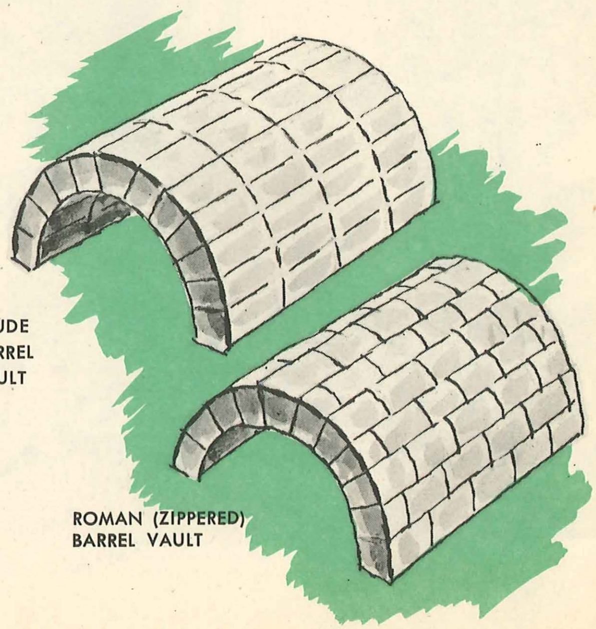
But there were places where the lintel method did not work so well. In the dry hot regions of the Middle East,



The heavy two-level stone roof of the Great Hypostyle Hall in the temple of Ammon at Karnak was supported by 134 columns arranged in 16 rows. The central rows of columns were 80 feet high.

there were few trees, and it was hard to find timbers that would support heavy roofs. The builders wanted to construct heavy roofs to keep out the sun's blazing heat. So they invented *vaults* and *domes,* three-dimensional true arches.

Suppose you had a room 15 feet wide and 30 feet long, with strong stone walls, and you wanted to put a brick or stone roof over it. You could build a true arch 15 feet wide from wall to wall over one end of the room, then another arch right alongside it, and another, and so on for 30 feet, until the whole room was covered. You would then have a crude vault. You could make it much stronger by interlocking the bricks the way they are zippered together in an ordinary stone wall.



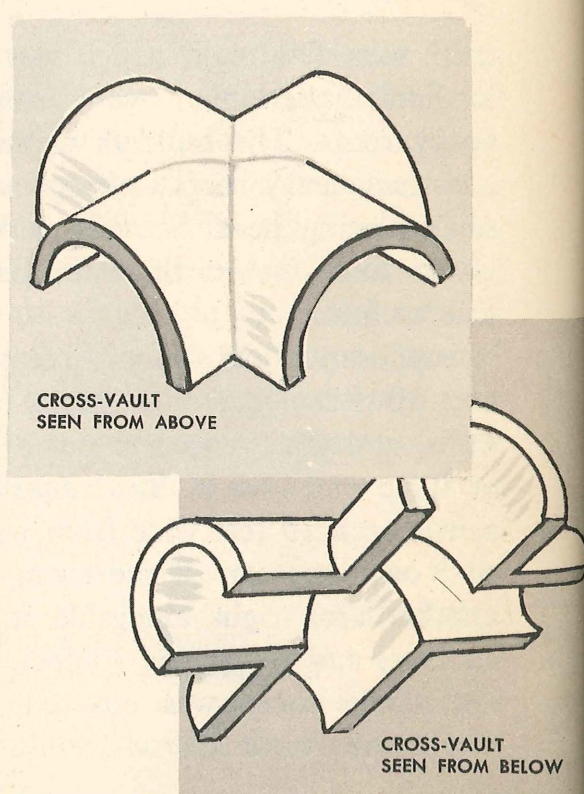
Suppose you had a round room. You could then make your roofing bricks wedge-shaped from side to side as well as up and down, so each course would be laid in a circle and at the same time, as the rings of brick went higher, they would curve over like the stones of a true arch. You would then have a dome.

The imperial Romans were great builders of vaults and domes. They discovered that by mixing a certain kind of earth with calcium hydroxide (made from limestone and water) they could make a concrete that was as hard as stone. Since the Romans' conquering legions captured many slaves, this material was particularly useful. Only a few skilled workers were needed to build "forms" or curved molds out of wood and then to build thin, strong arches out of tiles or bricks inside them. Then hundreds of unskilled slaves could simply climb up with buckets of wet concrete and pour it into the forms. When the concrete hardened, the wooden forms were ripped away, and there stood the vault or dome, just as if it were made of one slab of stone. The tile arches strengthened it just as your ribs strengthen your chest and keep your lungs from caving in. The slaves did not have to be treated well, because if any of them died, other slaves could be put to work without the master having to waste any time or trouble training them. Nowadays, we sometimes boast of how many dollars something cost us. In ancient times, rulers often boasted of how many *lives* things cost.

What are Roman cross-vaults?

The Romans also discovered that they could make vaults cross through each other. Instead of collapsing at the corners where the vaults came together at right angles, these *cross-vaults* were actually stronger. Their corners acted like rib-

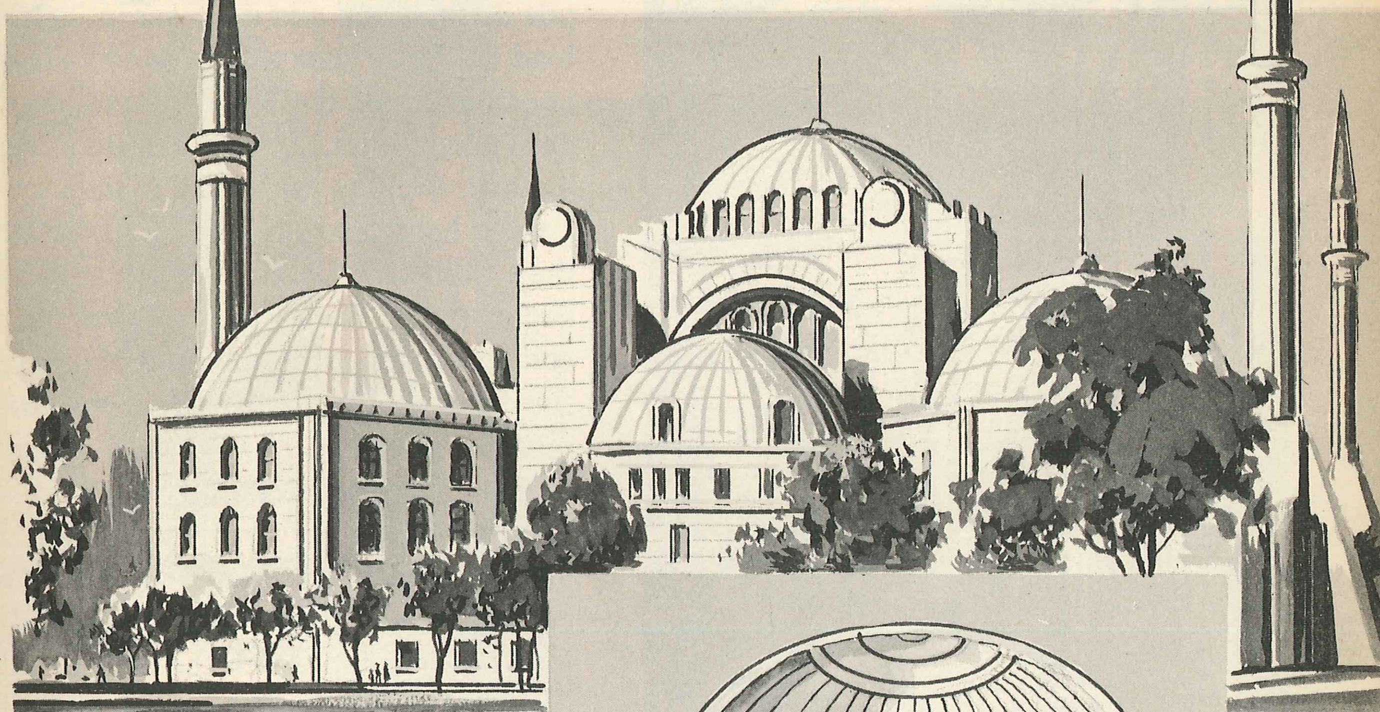
The Catacombs in Rome were huge underground vaults, used by the early Christians as assembly places. They buried their dead in the walls.



arches. This discovery was one of the most important in the history of building, but it took a thousand years for builders to realize what it meant.

In that thousand years, the mighty Roman Empire grew weaker and weaker. At last it was conquered by tribesmen from the east and north — the tribesmen who had been started on angry wanderings back and forth through Europe by the cruel invasions of the Hsiung-Nu Horde. But in the

The Santa Sophia in Byzantium, renamed Constantinople and capital of Roman Empire in A.D. 330 by Constantine, was built in 532-537 and, with her onion-shaped domes, is one of most famous Byzantine style churches.



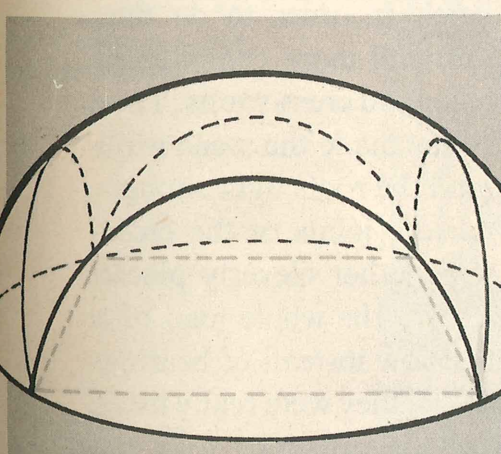
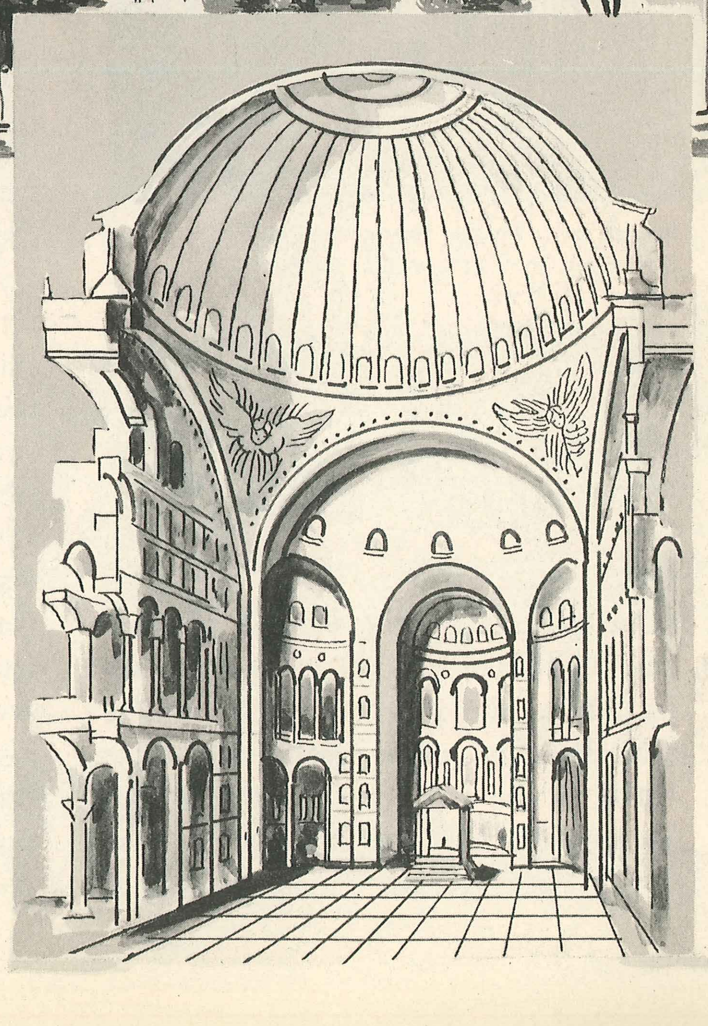
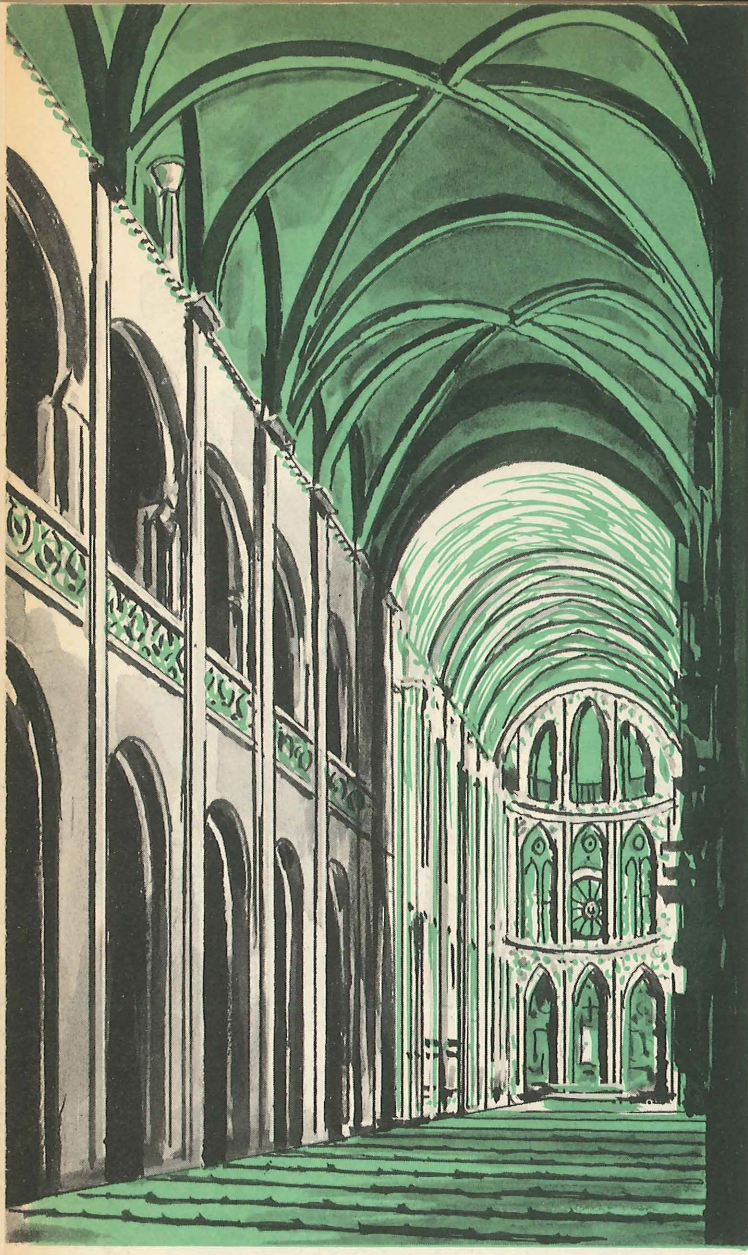


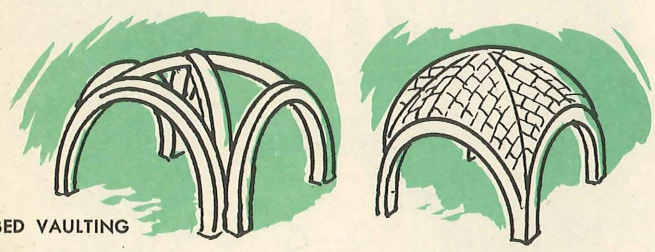
Diagram of the construction of a dome.



The interior of the great dome of the Santa Sophia is built of brick and concrete. It rises 180 feet above the ground and is 107 feet in diameter.



Interior of a French Romanesque church in Caen, Normandy, showing beautiful ribbed vaults.



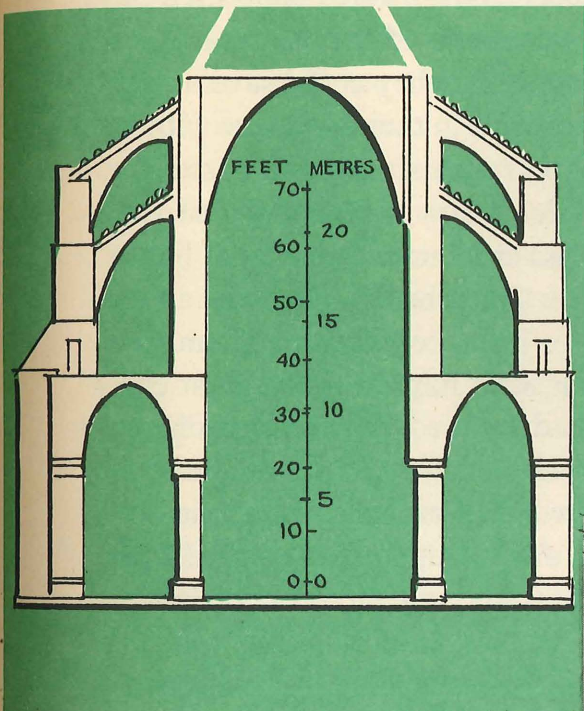
RIBBED VAULTING

same thousand years, Roman missionaries had brought Christianity and civilization to the northern peoples. The churches and other grand structures built in the cold northern parts of Europe during the Middle Ages were copied from Roman designs. But the master builders had to change those designs. For one thing, there was more snow. The taller the building, the more room there would be for windows to let the sunlight in. The narrower the building, the nearer everything inside of it would be to a window. The steeper the slope of the roof, the less snow would pile up on it and add a dangerous extra load to the structure. Of course, when the builders of the Middle Ages were designing castles, they were more interested in keeping out enemies than letting in light, and in spite of the snow they designed flat roofs that archers could shoot from. But in designing cathedrals, the great buildings of peace, they used all the discoveries of the Romans in wonderful new ways.

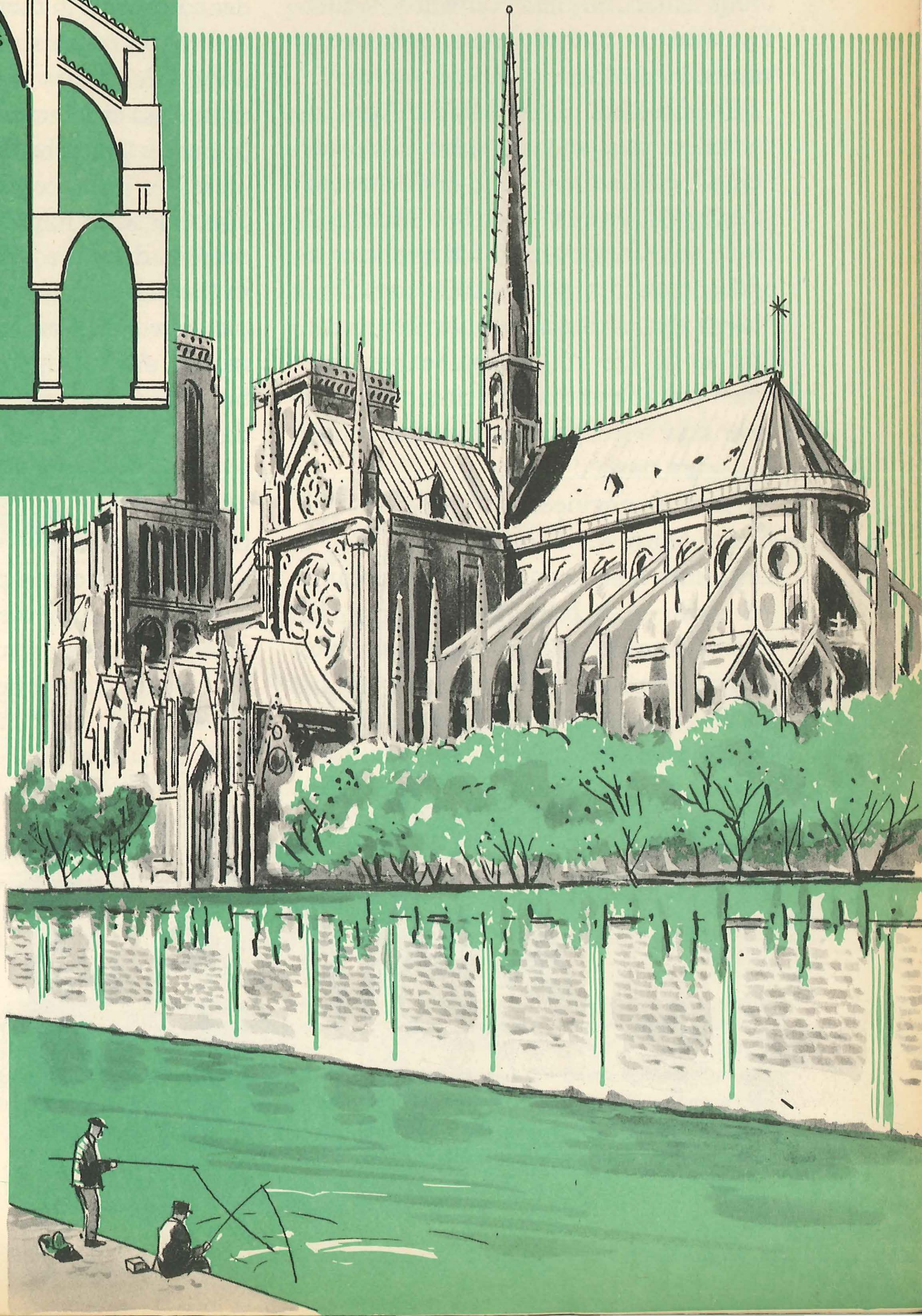
They built their tall noble cathedrals with glorious huge windows of colored glass to remind the worshippers of the beauty that God had made, and with high towers from which the bells could call across the countryside to remind workers to pray. In order to do this, they used more and more complicated systems of arches and cross-vaults. They found that if they made the stone walls thin enough and the roofs light enough, they could use the joints of the cross-vaults and some other cleverly placed rib-arches to carry the whole load of a vast structure. Now instead of bearing-wall construction, they were really using frame-and-skin construction, with the frames made out of magnificent stone arches and the skins made out of stone, tile and glass. These were the first great frame-and-skin designs in history, and some of the finest works man had ever created with stone.

How did the Gothic arch and flying buttress help the northern builders?

The finer the work, the more difficult are the problems. A true arch or a vault carries a load down around an open space. In doing so, it thrusts sideways. If you stand on roller skates with your toes pointing outward, you will find that you can stand comfortably as long as your feet are close together, but if you make an arch of your legs, the load of your weight will force your feet wider apart, and the wider apart they get the stronger the sideward thrust, and of course the nearer your body will get to the ground. If you can get a friend to



A section through the nave of London's famous Westminster Abbey, showing the vaulting and buttresses.


One of the most famous examples of the use of flying buttresses and Gothic arches is Notre Dame, the beautiful cathedral of Paris, France.

stand next to you on skates the same way, with the toe of his left skate against the toe of your right, your right and his left foot will be braced, but you will still have trouble with your left foot and he will have trouble with his right. In exactly the same way, a row of arches will help to keep one another up but the two end arches may collapse unless something balances their outward thrust. The same is true of vaults, even cross-vaults.

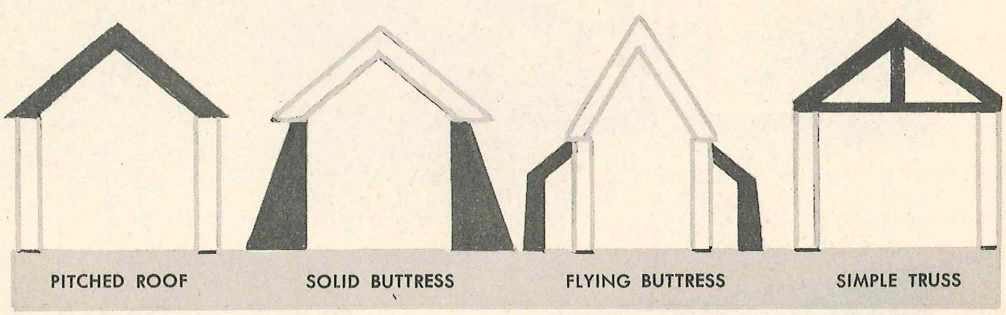
The builders of the Middle Ages invented various ways to solve this problem. One was the *Gothic arch.* Instead of sweeping over a space in a wide half-circle, the Gothic arch is tall and narrow and comes to a point at the top. This means that it has less outward thrust, just as in the roller-skate experiment when you found that the closer together your legs were, the less forcefully your feet were pushed apart.

Another engineering device was the *flying buttress.* This was like half a Gothic arch propping up a high column or vault, and helping to "carry the thrust" down to the ground. Sometimes a flying buttress was propped up by another, lower flying buttress, and this by yet another.

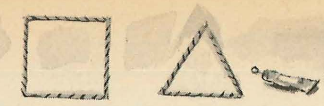
What kind of an engineering device was the truss?

A much more important engineering device was the *truss.* This made it possible to cut down some of the load at the top of the structures. The Λ-shaped roofs were supported by wooden beams, and the master builders discovered that they could save a great deal of weight in their structure without losing too much strength if, instead of using thick heavy, beams they used the right criss-cross arrangements of lighter beams or "members." This was an old idea. For instance, the Roman emperor Hadrian, who himself was a great engineer, had used a very clever roof-truss in the entrance-way of the famous temple called the Pantheon, which he built in 130 A.D. But in the Middle Ages, builders found out more about how to design trusses, and it really was this study of trusses that led to the discovery of a great deal of the modern science of civil engineering.

The two most important ideas in designing a truss are these: 1. Force should always go *along* a member, not across it: a beam should be pushed or pulled, but not bent. 2. The triangle is naturally stiff; it is the only geometrical figure

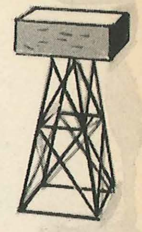


The walls of a building not only have to support the roof; when the roof is pitched they also have to withstand the thrust that tends to push out. Solid or flying buttresses counteract this thrust and give support to the walls. The truss is a simpler and more advanced engineering device to balance the forces.



whose angles cannot be changed without changing its sides.

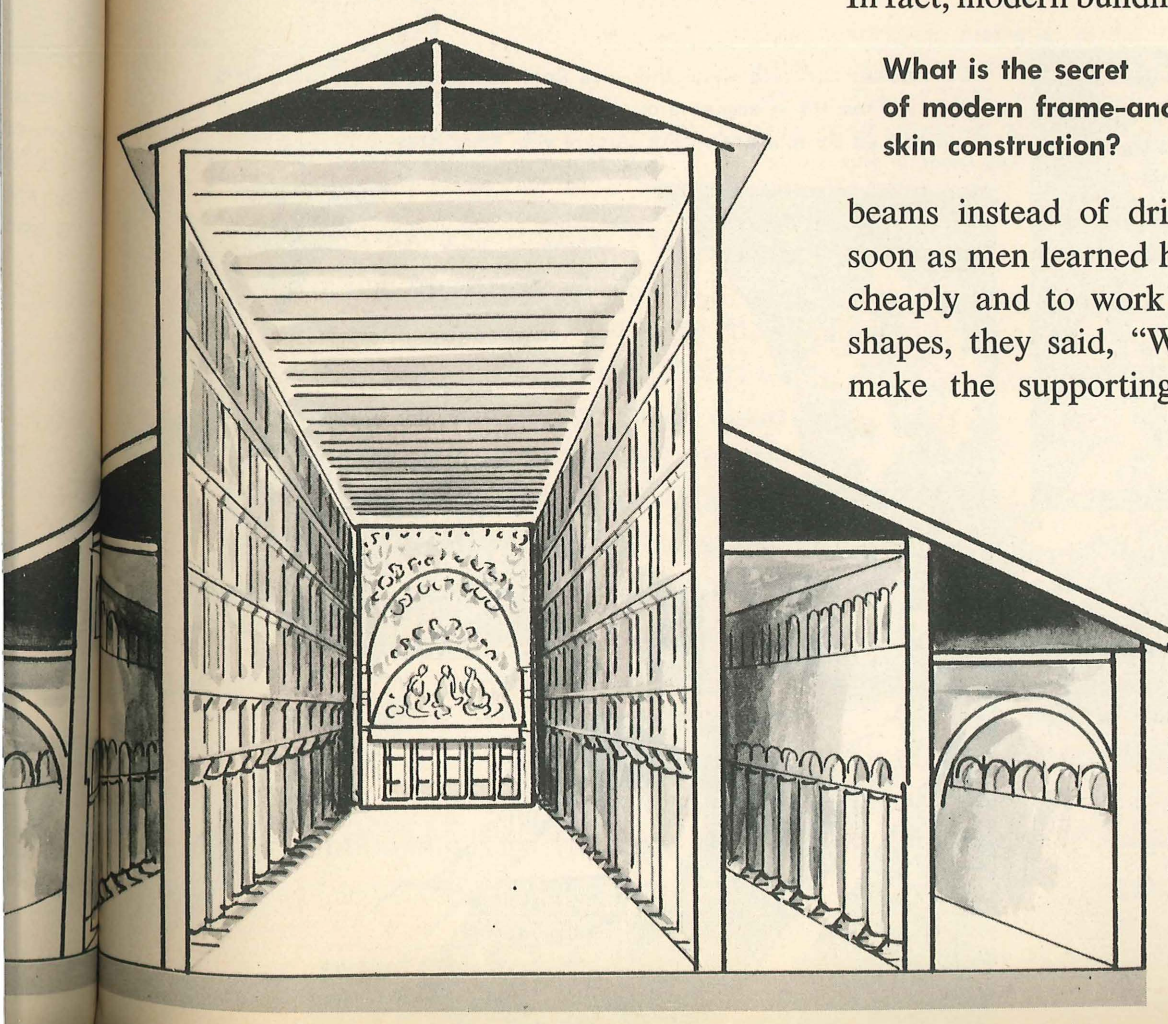
You can experiment for yourself with these principles, using model-airplane cement and drinking straws. First, arrange three straws in a triangle and attach their ends with cement. Then arrange four straws the same way in a square. You will see that the triangle will hold its shape unless a straw breaks or unless a corner comes completely apart. But you can easily squeeze the square out of shape without breaking a straw, and you will notice that its corners quickly come unstuck as a result. Now, hold the triangle upright and think of it as a set of beams bracing a roof. As long as the two sloping straws (the *rafters*) do not bend, the roof is safe. The tensile strength of the straw across the bottom keeps it from sliding out flat. But suppose you are afraid that the weight of the roof-covering will make the rafters sag. Is there some way you can glue in some pieces of drinking-straw so as to carry some of the load *along* these members instead of *across* the rafter-straws? You will probably be surprised to discover which designs work well and which do not, but when you think about them you can always find out why.



You can now do a much more modern set of experiments. Following the same two principles, try to build a strong tower out of straws and model cement. If you can build a drinking-straw tower 8 inches high which will bear the weight of an ordinary brick, you may have the makings of a structural engineer.

What is the secret of modern frame-and-skin construction?

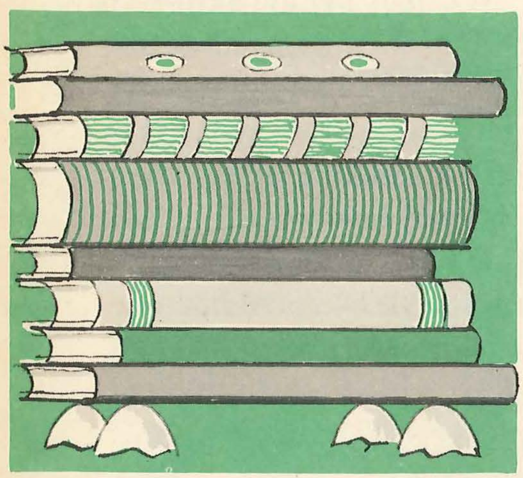
In fact, modern building began with just that experiment, but it was carried out with iron beams instead of drinking-straws. As soon as men learned how to make iron cheaply and to work it into the right shapes, they said, "Why shouldn't we make the supporting frames of our



The perspective section of old St. Peter's Church in Rome, built in 330 A.D., shows clearly the relatively simple truss structure.

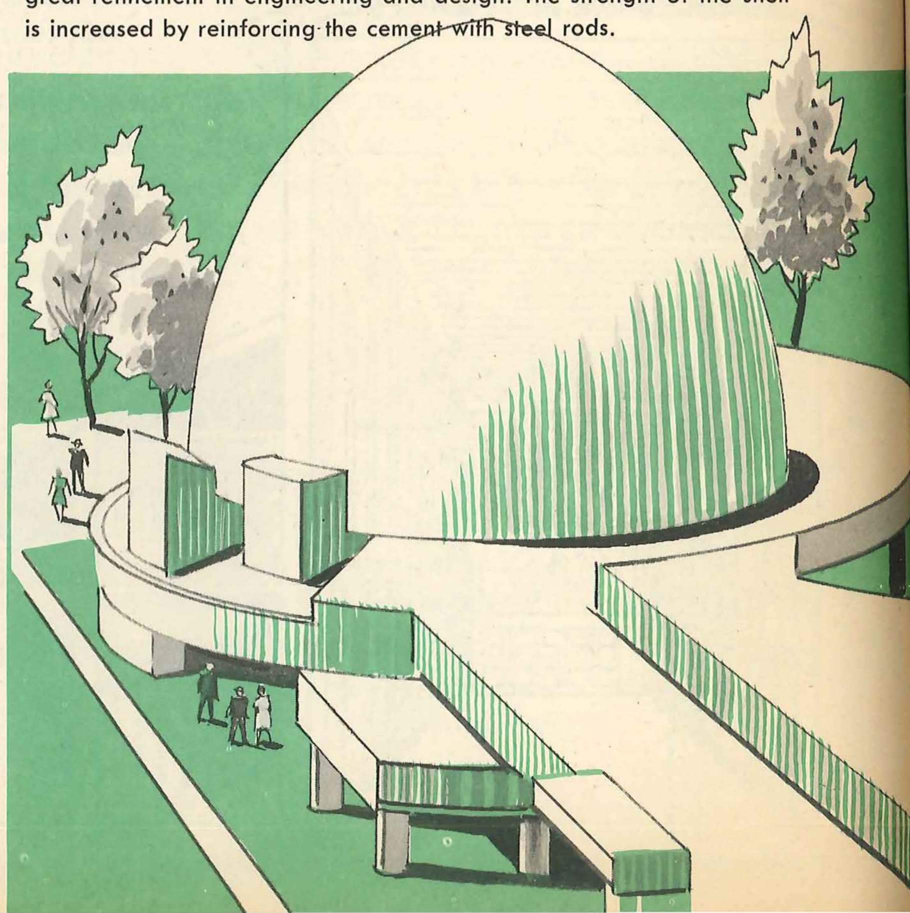
buildings out of iron? Why not make the whole frame like a big truss?" In 1851, a great exhibition was held in London. One of its marvels was the Crystal Palace, a huge building covering 20 acres, made of an iron skeleton with walls and roof of glass. Ordinary buildings began to be built with iron frames covered with brick or stone. The walls carried their own weight, but the frames carried the rest of the load. Then came the work of a French engineer named Alexandre Gustave Eiffel, designer of the iron frame for the Statue of Liberty. He also dreamed of building an iron-frame tower 1,000 feet high — no one had ever built a structure that tall — and he carefully experimented and made plans. His plans were so carefully drawn that, when the Eiffel Tower was built in Paris in 1889, out of 12,000 iron members connected by 2,500,000 rivets there was not a change in the plans, not a mistake in the construction, not an accident, not a delay.

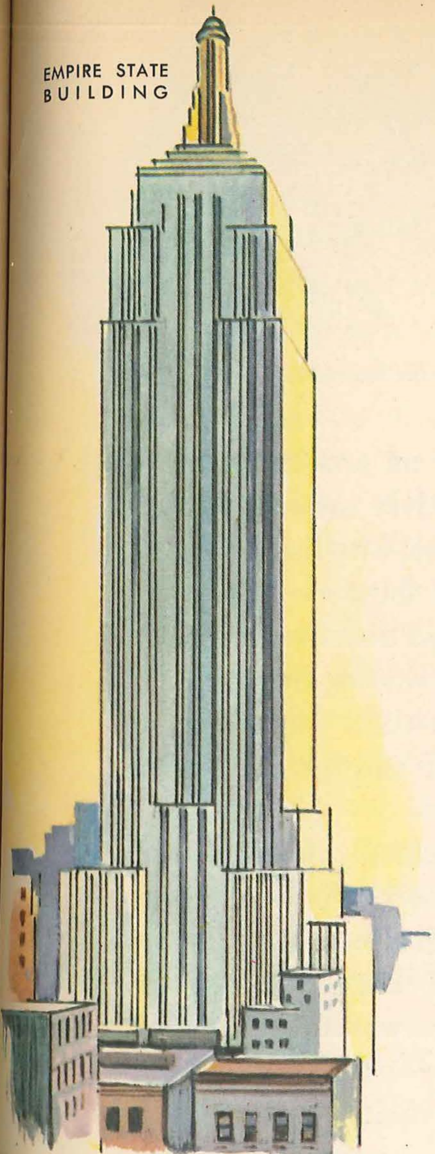
From that time on, the biggest buildings were of frame-and-skin construction like the Indian's teepee or the cannibal's hut. The frames were of steel. The skins, mounted on the frames, were of stone, brick, metal, and glass. The Empire State Building in New York — 102 stories high with a 220-foot television tower on top, reaching 1472 feet into the air — weighs 302,000 tons, including 67,000 tons of steel. The load on the hundred thick steel columns of the frame is so huge that between the ground and the 85th floor they are actually squeezed 6½ inches shorter than they were when they were made. The skin is made with 13,000,000 bricks and 2,000,000 square feet of limestone facing. The fact that such a building could



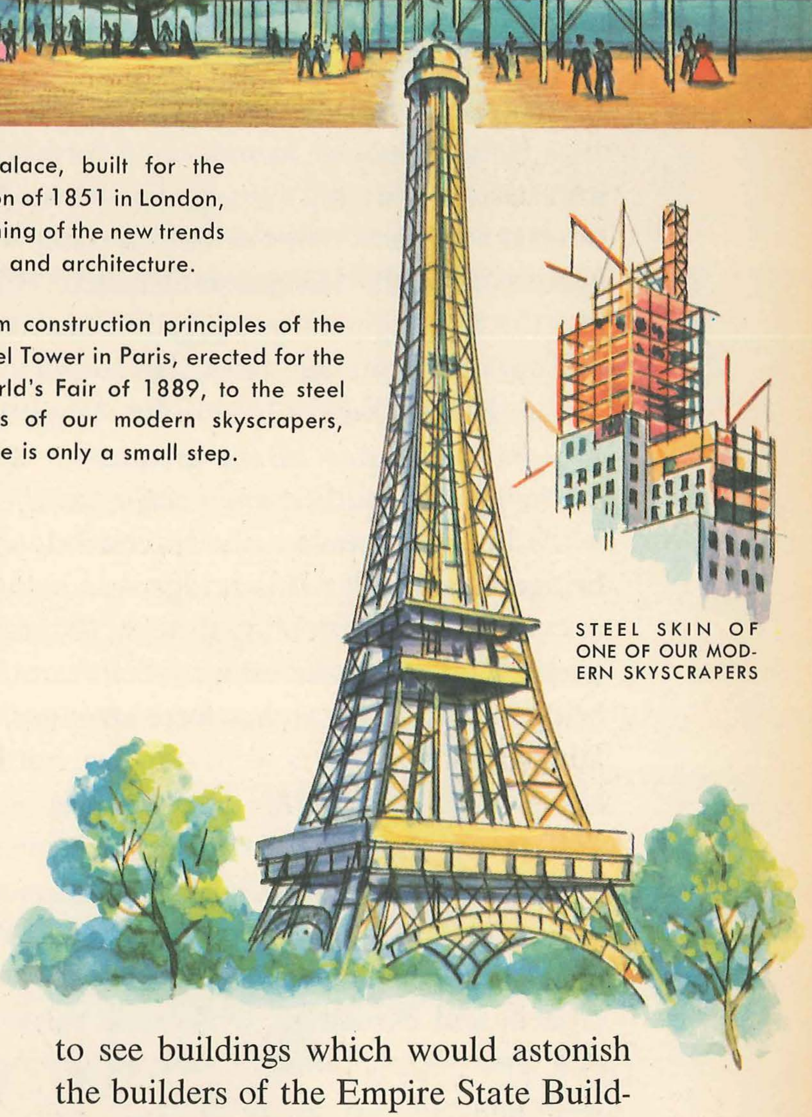
You can easily test how strong the shell design is, by taking four half eggshells and using them as corners for a "book-tower" as the illustration shows you. You will be surprised how much weight it takes before the shells are crushed. Make the halves as even as possible in height and as smooth as possible on the rims.

The modern concrete shell, thin and light compared to its span, is a great refinement in engineering and design. The strength of the shell is increased by reinforcing the cement with steel rods.





The Crystal Palace, built for the Great Exhibition of 1851 in London, was the beginning of the new trends in engineering and architecture.

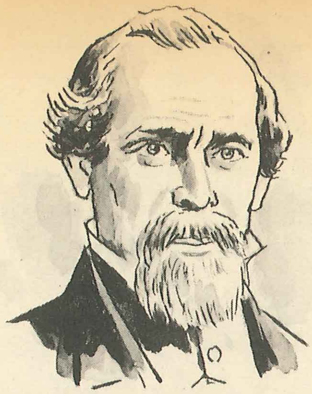


From construction principles of the Eiffel Tower in Paris, erected for the World's Fair of 1889, to the steel skins of our modern skyscrapers, there is only a small step.

STEEL SKIN OF ONE OF OUR MODERN SKYSCRAPERS

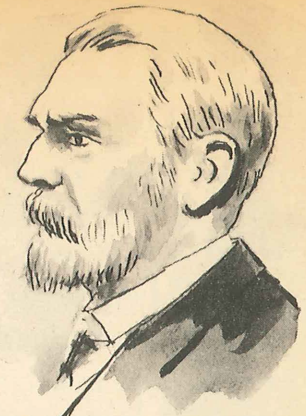
even stand up would seem like magic to Daedalus, until four thousand years of engineering were explained to him.

But the story does not end there; in engineering no story ever ends. Even now we are learning to use old materials in new ways and new materials in old ways. We use *reinforced concrete,* concrete with steel rods running through it, so that it will have the compressive strength of concrete and the tensile strength of steel. We can cast concrete domes many times larger than any Roman emperor ever dreamed of building. We can build huge structures out of thin shells of concrete. Perhaps you will live to see buildings which would astonish the builders of the Empire State Building the way Knossos astonished the shipwrecked shepherd.



JOHN AUGUSTUS ROEBLING

THE BROOKLYN BRIDGE



WASHINGTON AUGUSTUS ROEBLING

On a summer day in 1869, two men were standing on a dock near the lower end of Manhattan Island, looking across the East River towards Brooklyn. They did not notice the rattle and shouting of New York City behind them. The sea gulls swayed and soared lazily overhead, and the ships moved in and out of the busy harbor with black smoke billowing through their bare rigging, and the two men paid no attention. The younger of the two was looking through the small brass telescope of a surveyor's transit, and the older stood on the edge of the dock squinting over the Brooklyn waterfront and now and then glancing thoughtfully at a little notebook in his hand.

Neither looked around as a ferryboat loomed up next to them and slid into its dock, its big round nose bumping the slimy timbers. The older man uttered a cry and fell, twisting in pain. A leaning timber had crushed his foot against the dock. His assistant called, "Come help Mr. Roebling! He is hurt!" and the fainting man was taken to his son's house in Brooklyn. Surgeons came and cut off the mangled toes, but it was too late. The terrible disease of lockjaw set in, and two weeks later John Augustus Roebling was dead.

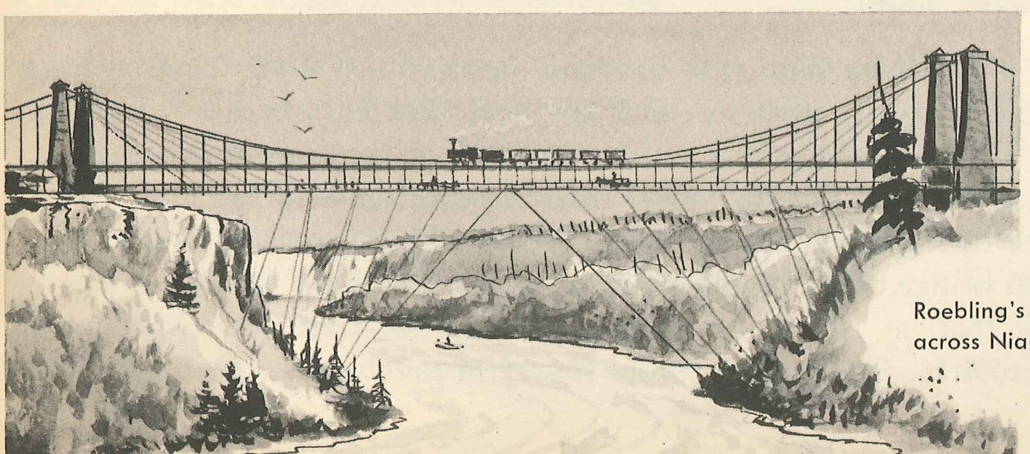
Roebling, one of the greatest bridge-designers of all time, was born in Germany and studied engineering at the Royal Polytechnic in Berlin. Once, while he was a student, he traveled down to Bavaria to watch an interesting bridge being built. This bridge was held up by iron chains hung from towers at each end, and Roebling thought to himself, "*This* is the way to build a bridge over wide deep water where tall ships must sail!" Other engineers might think bridges held up by arches were stronger, or that bridges of heavy iron frames laid across stone piers were steadier, but he, Roebling, would hang great spans across wide spaces with strong cables fastened to towers.

It was the cables for these "suspension bridges" that worried him, for he knew that iron chains could not be made strong enough. But what could he use instead of chains? He was still thinking about this problem when he came to America as a young man of twenty-five. He married, became an American citizen, and earned his living as a surveyor. One day, while surveying in the Allegheny Mountains, he saw an accident. In those times, canal boats were an important way of traveling, and the heavy crafts were hauled from canal to canal on tracks over the mountains. A rope broke, and the boat it was pulling plunged down a mountainside killing two men. Roebling asked himself, "Couldn't they make ropes out of something stronger than hemp fiber?" And suddenly he saw that he had solved the problem of bridge cables. He would weave ropes out of iron wire!

So he built a rope-twisting machine in his backyard; he bought some iron wire and went into business, selling his new wire-rope to canal-boat companies. His business was a success. Then he moved to New Jersey and built a factory that used machinery he designed himself. Even today, if you should happen to see a big reel of cable near some construction, look at the manufacturer's name. It may very well be John A. Roebling's Sons.

The oldest of John A. Roebling's sons was named Washington Augustus Roebling and, like his father, became an engineering student. He, too, loved bridges, and hoped to join his father in building them. For John Roebling's dream had at last come true. After building some small bridges and showing that his wire cable could make suspension bridges strong and steady, he tried to get the job of building the railroad bridge across Niagara Falls. Another engineer got the job but could not do it, and Roebling was called in. His plan was a daring one, for suspension bridges bend and swing much more than other kinds, and most engineers were sure that the rough northern winds and rushing locomotives would wrench the structure apart. However, by cleverly using his cables to steady the 822-foot span, he built a bridge out of wood and wire that was one of the marvels of its time. More engineers began to build suspension bridges following John Roebling's designs.

Washington Roebling became his father's partner, but not for long. The Civil War broke out, and the young engineer enlisted, built bridges for Mr. Lincoln's armies, became a colonel, married the daughter of his commanding officer, and after the war joined his father again. Soon John Roebling was asked to build a bridge from Manhattan Island to Brooklyn, for although New York was already becoming one of the great seaports of the world, it was still a group of separate towns watching each other across rivers. Washington Roebling moved to Brooklyn with his bride Emily, and father and son began to study the problem.

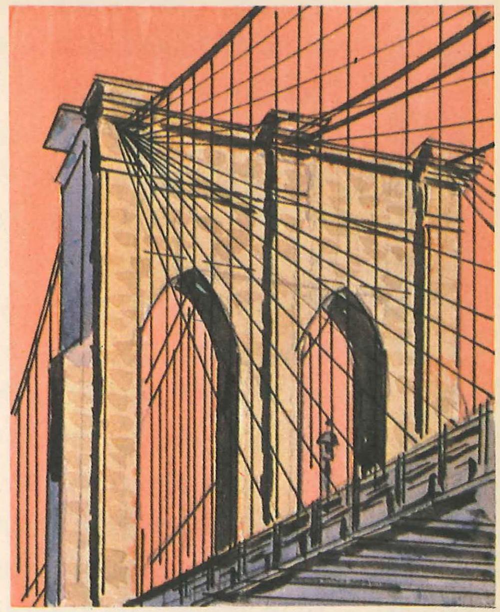


Roebling's railroad bridge across Niagara Falls.

March, 1877: building of the Brooklyn Bridge from the Brooklyn side.

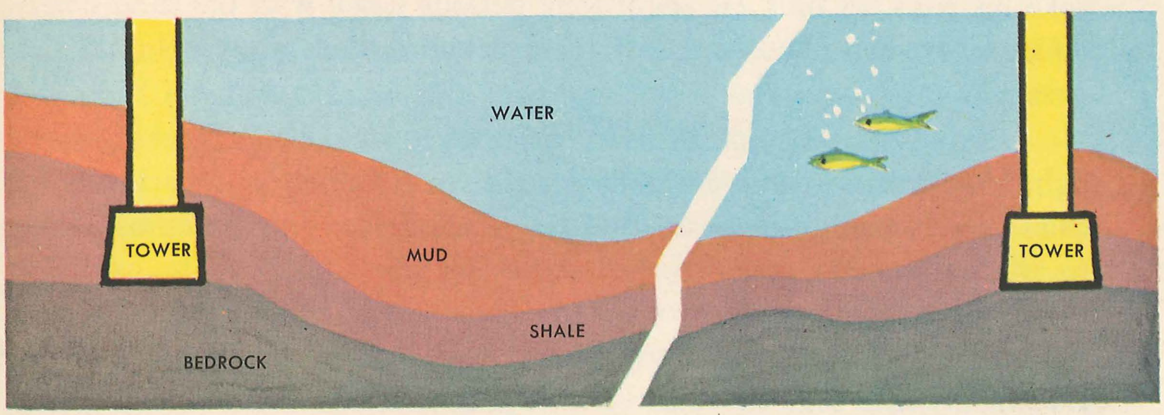
The ocean-going ships with their tall masts passed along the East River day and night, and the river was wide and deep. The Roeblings saw that their Brooklyn Bridge would have to have one high, long span, nearly twice as long as the Niagara span, and far longer than any span anyone had ever tried to build. The Roeblings would now show the world how beautiful and strong a suspension bridge could be. The great towers would have to be built on the hard rock that lay under the muddy banks of the river — so Washington Roebling took his Emily off to Europe for a year to look at suspension bridges,

Larger and longer bridges were built since the opening of the Brooklyn Bridge between Brooklyn, at the left, and Manhattan, at the right. Few became as famous as this last stone-towered suspension bridge.



The close-up view of one of the towers shows the complicated pattern formed by the steel suspension cables.

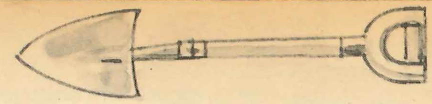
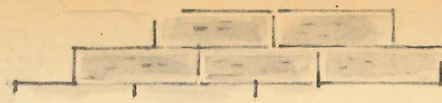
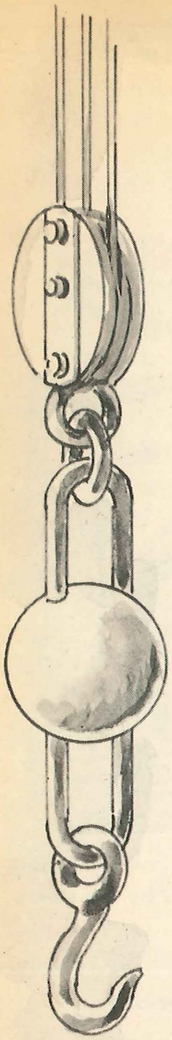
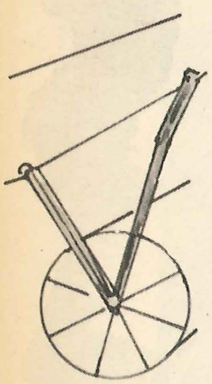
Vertical section through the river bed showing the difficulties to be overcome to build the concrete towers.



and then returned and boarded a train for St. Louis to see how an engineer named Eads was building underwater foundations for a bridge across the Mississippi River. John Roebling stayed in New York, surveying, designing, planning, talking to politicians and bankers, preparing to build his masterpiece.

And just as work was about to start, John Roebling went down to the docks to check the surveyors' measurements once more, and did not notice the ferry coming in. . . .

So Colonel Washington Augustus Roebling, only 32 years old, became

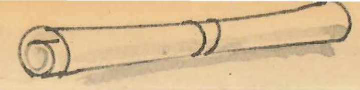
chief engineer of the great bridge that his father had designed. The world would see what an engineer John Roebling had been!

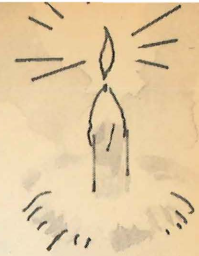
He decided that the best way to build solid foundations for the huge granite towers was to use a device called the *pneumatic caisson*. This was a kind of huge box stiffened with iron and cement, and open at the bottom. It was set down in the mud, and the granite blocks of the foundation were built on top of it layer by layer, leaving a shaft down the middle. Down this shaft went the workmen, called "sand hogs," with picks and shovels to scoop away the earth under the edge of the box, so that it sank lower and lower. And up the shaft came the sand and clay, pulled up by powerful machines and loaded into barges to be taken away. But there was one big difficulty — how to keep water from flowing in under the edge, filling the caisson, and drowning the men. This was done by pumping compressed air into the caisson, so that the push of the air trying to get out of the box was always stronger than the push of the water trying to get in. That meant, of course, that the deeper down in water and mud the caisson had to go, the greater the air pressure inside had to be. Out in St. Louis, Eads had found that if the pressure grew too high, men would be crippled or die horribly of what was called "the bends" or "caisson disease." A Doctor Jaminet was working on this problem, but had not yet solved it. Washington Roebling knew that one of his caissons, the Manhattan one, would have to go down more than 70 feet. But he had to take the risk.

The young chief engineer was not the kind of man who sent others to take his risks for him. He spent long periods down with the sand hogs in the caissons, though it was not safe to work more than a few hours in the compressed air.

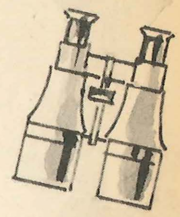
At that time, Thomas Edison had not yet succeeded in making an electric light that worked, and ordinary rooms were lighted by gas lamps. In the caissons this kind of lamp was dangerous. For one thing, the pressure seemed to affect the men's noses so they could not smell leaks of the explosive gas. For another thing, the heat of the gas flames made the air too hot to work in. Oil lamps smoked too much. The sand hogs usually used candles set close to the places where their shovels were swinging. But any kind of flame is dangerous in compressed air, and early in 1872 the Brooklyn caisson caught fire. From ten at night to five in the morning, Washington Roebling stayed in the compressed air, leading the desperate efforts to save the structure, and it was saved. But in May of that year, he was carried out of the Manhattan caisson, unconscious from "the bends," and for a night his life seemed to be flickering out. A few days later, he said he felt perfectly all right and went down again. Again he was carried out, this time crippled for life at the age of thirty-five.

But he was still chief engineer. Every movement of his twisted body cost him a terrific effort, but he would finish his father's masterpiece. Sitting in a

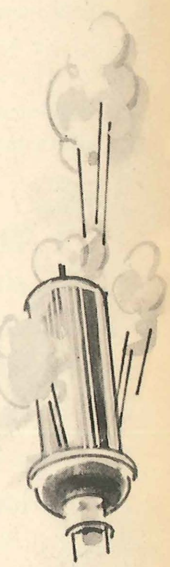




chair at a window in his house, he watched the work through field-glasses. He made drawings and wrote orders, and his wife Emily took them to the workers on the bridge. She studied books on civil engineering and took lessons from her husband so that she could be a good assistant to him.



The Brooklyn caisson came to rest 44 feet under the river. The Manhattan caisson, the largest ever built up to that time, had to work its way through quicksand and finally settled on a ledge 78 feet down. The towers began to rise. They rose 266 feet above the water, and then the stringing of the wire began. This wire was made of steel, a specially processed iron which is stronger and lighter than ordinary iron. At that time, using steel for building was a new idea. But new ideas were what made life worth living for the crippled engineer sitting at the window.



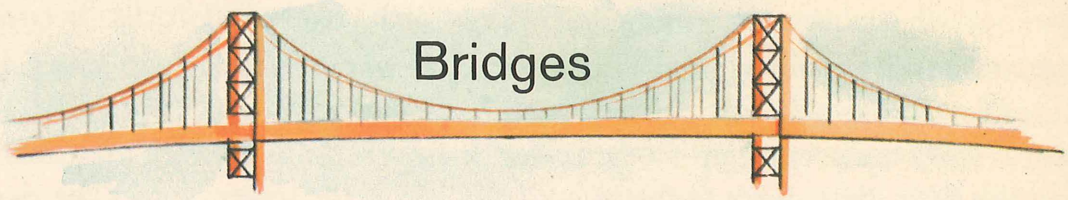
A slender footbridge was hung between the towers, and in May, 1877, a five-foot wheel began traveling back and forth, back and forth, between Manhattan and Brooklyn, unrolling wire. The wheel made a trip every ten minutes for a year and a half. Each length of wire went back and forth 278 times — from the ground up to the tower, then down and up in a great curve across the river, then down to the ground, and up to the tower, across the river, down to the ground — and when the whole length of wire was hung in place and looped around iron anchor-bars at each end, the 278 thicknesses were wrapped into a tight bundle. When 19 bundles were in place, they were wrapped into a cable. There were four cables, which together had a strength of 18,000,000 pounds. Two highways, two railways, and a wide walk were hung from these cables.

In 1882, jealous rivals and politicians tried to have Washington Roebling fired as chief engineer. Emily Roebling went to a meeting of the American Society of Civil Engineers to make a speech. She told the engineers all that her husband had done and all that he had lost, and the engineers rallied to him. He remained chief engineer of the bridge which had been the dream of his father's life.

On May 24, 1883, Washington Roebling sat waiting at his window in Brooklyn. Emily stood beside him. They watched the great bridge, completed but deserted. From across the river came the faint sounds of bands and cheering. Then a great procession moved along Broadway and swung onto the beautiful long span. Emily helped her husband focus the field glasses. "There they are, Emily, there they are!" said the engineer. Three men in silk hats and frock coats stepped proudly side by side at the head of the parade — the Mayor of New York City, the Governor of the State of New York, and the President of the United States. On the river below them, the sirens of the boats bellowed their applause. Cannons boomed. Church bells jangled. Factory-whistles screeched. Tens of thousands of human throats poured forth cheers. Nearer and nearer came the marchers, until they were out of sight below the window where Washington Roebling sat. A moment later, there was a knock on the door of the room. Emily ran to open it.

Three men stepped into the room — the Mayor, the Governor, and the President — while a dozen others crowded the doorway and watched. "Mr. President," said the Mayor, "may I introduce Colonel Roebling?" The President took the crippled man's trembling hand in both his own. "It is a privilege to meet a brave leader and a brave builder," he said. Outside, the fireworks were starting and the happy crowds were swarming over the bridge.

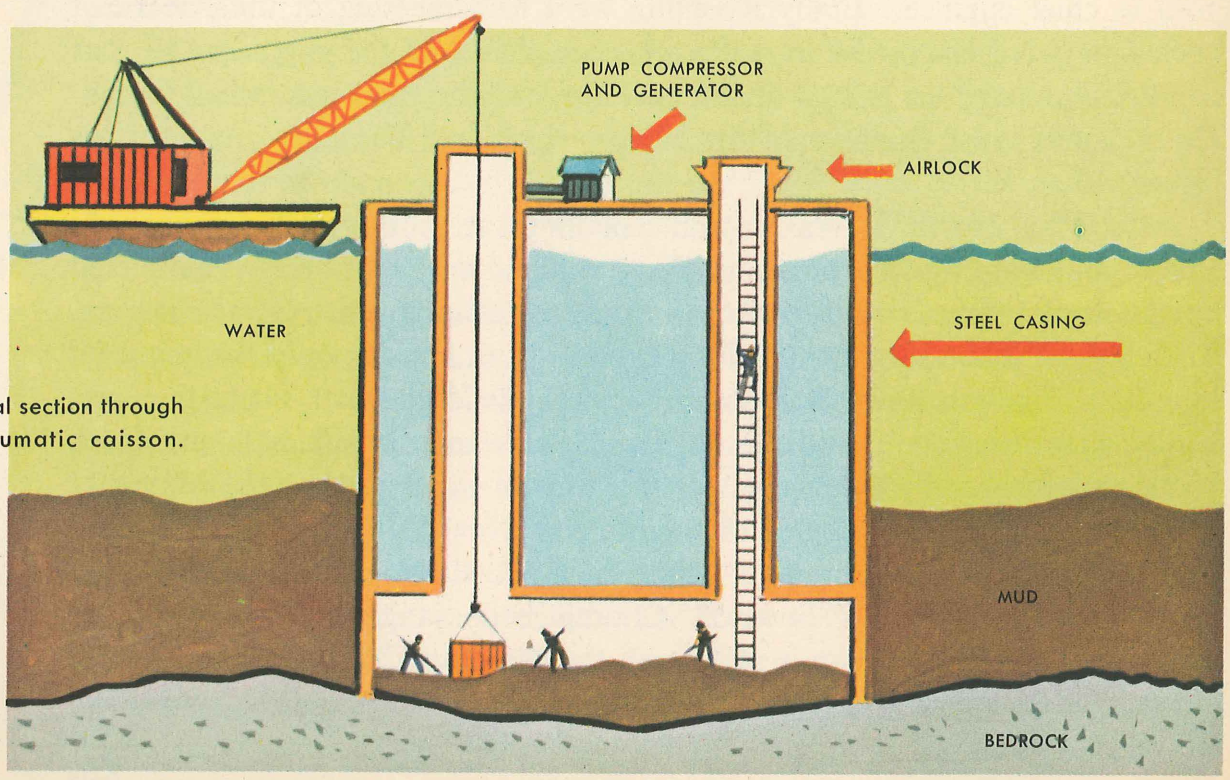
That is the true story of one of the greatest bridges ever built. Crowds still swarm across the Brooklyn Bridge, thousands upon thousands, every day, and John Roebling's ideas can be seen in thousands of other suspension bridges all over the world.



Bridges

What problem does the live load pose?

The problem in designing a bridge is really the same as the problem in designing a doorway in a wall or a roof over a room. It is the problem of carrying a load over an open space. The load on a bridge is more than the *dead* weight of the structure itself. It is also the *live load* — the push of people and trains and cars moving across the bridge, and of winds blowing against it. The push of moving things can be surprisingly strong, even when the things themselves



Vertical section through a pneumatic caisson.

On November 7, 1940, a wind of over 35 miles an hour made the Tacoma Narrows Bridge in Washington swing and twist. Only four months after its completion, the structure was destroyed.

are light. Air, for instance, does not seem to be very heavy, but gales of air have blown down many large structures. The faster something moves, the harder it can push.

Can a bridge be "tuned" to a rhythm?

The *rhythm* of the pushing is also important. If you have ever pushed someone in a swing, you know how a series of very gentle pushes at the right moment will make the swing go back and forth in wild swoops. This is because the swing has a "natural" rhythm of its own (which depends on how long its ropes or chains are), and if the rhythm of the pushes matches this natural rhythm, the pushes will keep adding to the movement of the swing. Many kinds of structures, big and small, have natural rhythms of their own. A violin string has a very fast natural rhythm; its vibrations cause "sound waves" we can hear. The note it plays depends on how fast this rhythm is. Rhythm depends on how long and how tight the string is. You can do an experiment with a rubber band and an open cardboard box. Put the rubber band around the box so it crosses the open side — like a bridge. Then pluck the band. It makes a note. If you sing *exactly* that same note, you can make the rubber band quiver without touching it. Many bridges are also "tuned" to one rhythm of movement, of course, much too slow to cause sound waves. Soldiers are ordinarily supposed to march in step. But every army has a rule that when soldiers are crossing a bridge, they must march *out* of step, because the rhythm of the marching might just happen to be the natural rhythm of the bridge and the bridge might shake apart.

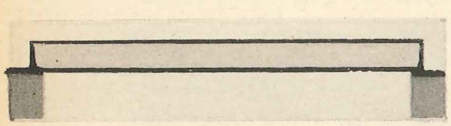
One of the most famous bridge disasters in modern times took place at Puget Sound, Washington. The Tacoma

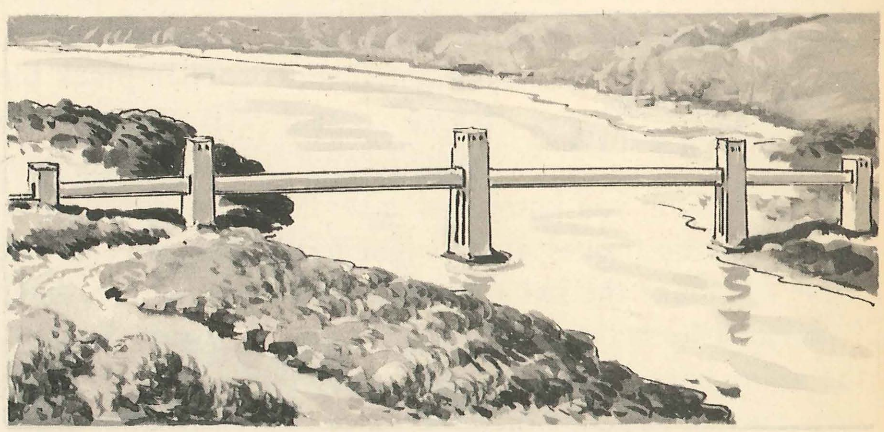
Narrows Bridge was completed there on July 1, 1940. It was a long suspension bridge, with some new engineering ideas in it. But its designers had forgotten some of John Roebling's ideas. The very first people to drive across the bridge noticed a strange waving motion, as if they were driving along the deck of a big ship in a stormy sea. This motion got very violent in high winds. People came to drive across "Galloping Gertie" instead of going to amusement parks to ride roller coasters. On November 7, 1940, only four months after the bridge was built, there was a very high wind. The bridge's bucking grew more and more violent. All traffic on it was stopped. Then the roadway started to twist around — first one side would tilt up until it was 28 feet higher than the other, then it would fall and the other would tilt up. At 11 o'clock in the morning, the span tore loose and plunged into the foaming water below. No one was killed, except a dog. The bridge had accidentally been "tuned" to a rhythm which happened to be the rhythm of the shaking caused by the wind when it blew at certain speeds against the steel girders and the edge of the roadway. If you press your two thumbs together side by side, with a blade of grass stretched in the slot between them, and blow with a certain force against the edge of the grass, it will make a shrill squeal. The roadway of Galloping Gertie vibrated the same way — only too hard.

To carry these live and dead loads across rivers and canyons, engineers design four types of structures employing the same principles as doors and roofs.

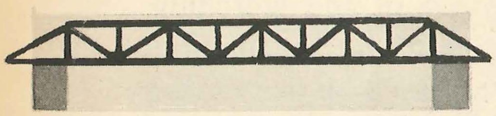
How is the beam bridge constructed?

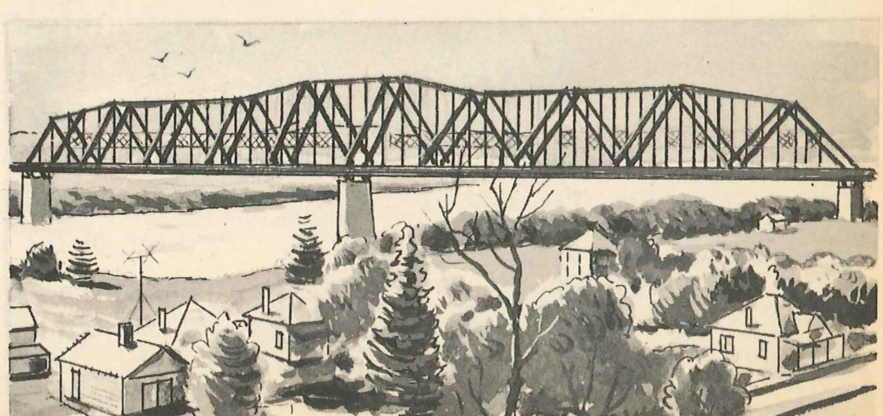
One, the *beam bridge,* uses the simple old lintel idea. In the times of the cave man, bridges were probably just logs laid across streams from bank to bank.





The principle of the simple beam bridge is utilized in the tubular Britannia Bridge over the Menai Strait in Wales.





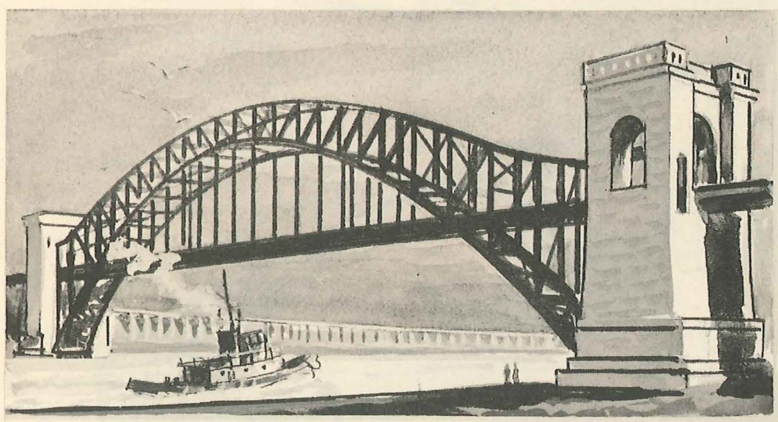
The truss principle adds strength with less weight. The Sciotoville Bridge across the Ohio River is such a continuous truss bridge.

Nowadays, in order to let boats go under a bridge, the beam is usually laid across the tops of columns or towers called *piers*. One of the first beam bridges made of metal was the famous and beautiful Britannia railway bridge in Wales, built between 1846 and 1850. It consists of two hollow iron beams laid across three towers, and the trains run *through* the beams. Most designers of beam bridges since then have used trusses — thin steel frameworks with criss-crossing braces to hold them stiff. Sometimes these truss-beams will hold up the roadway or railway from below. Sometimes they are above the roadway, like giant fences on each side. Sometimes, as you cross a trussed-beam bridge, you may even feel as if you were driving through a kind of truss-tunnel. In recent years, with better steel being made and with new ways of making reinforced concrete stronger, many engineers have been using "plate girders" and other solid beams to hold up roadways.

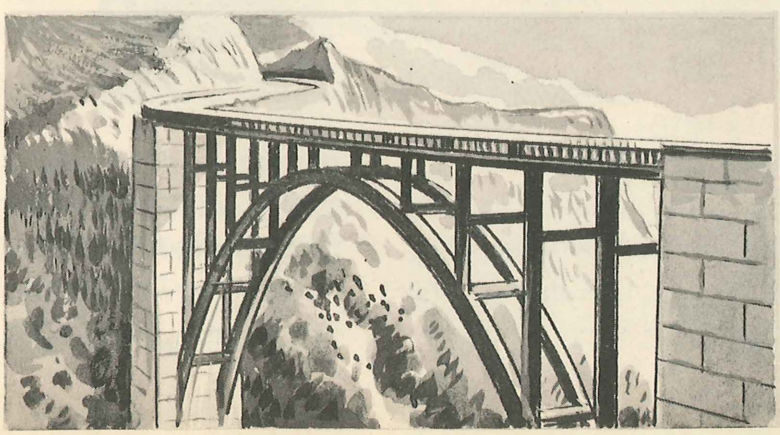
What are the characteristics of an arch span?

The second kind of bridge uses the *arch span*. Many arch-bridges built by the ancient Romans are still standing. They are just very thick walls running from river-bank to river-bank, so thick that men and wagons can travel along the top while the river runs through big half-circle arches below. Modern engineers use the arch in other ways too. Sometimes arch-shaped frameworks are used instead of straight trusses, bracing the roadway from underneath or at the sides. Sometimes the arched framework is overhead, and the roadway is hung from it.

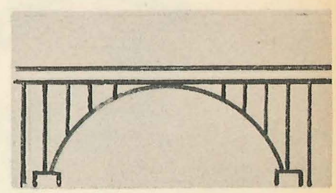
The first steel-arch bridge was built across the Mississippi River at St. Louis by one of the greatest of American engineers, Captain James Buchanan Eads.



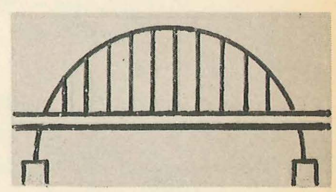
The Hell Gate Bridge over the East River in New York is one of the largest steel arch bridges in the world.



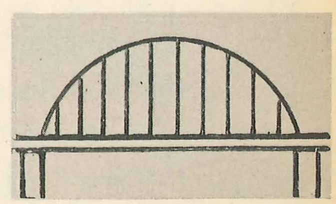
Near Carmel, California, stands the Rainbow Bridge, built with arches of reinforced concrete.



THE ROAD CAN GO ON TOP OF THE ARCH

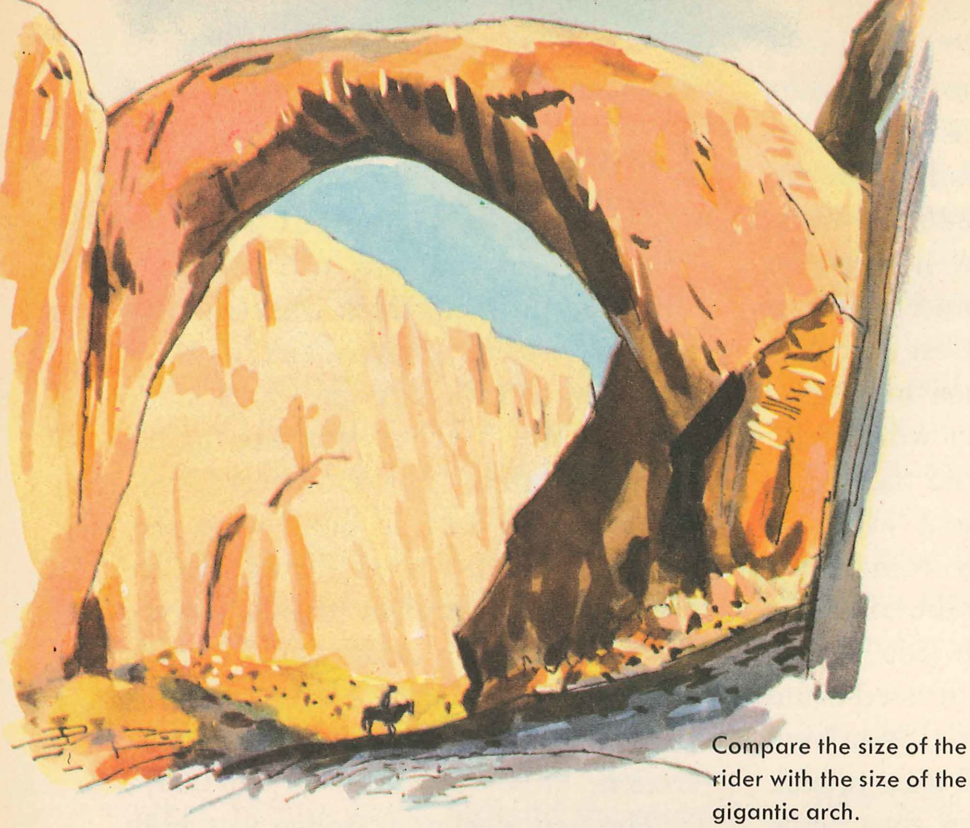


THE ROAD CAN GO THROUGH THE ARCH

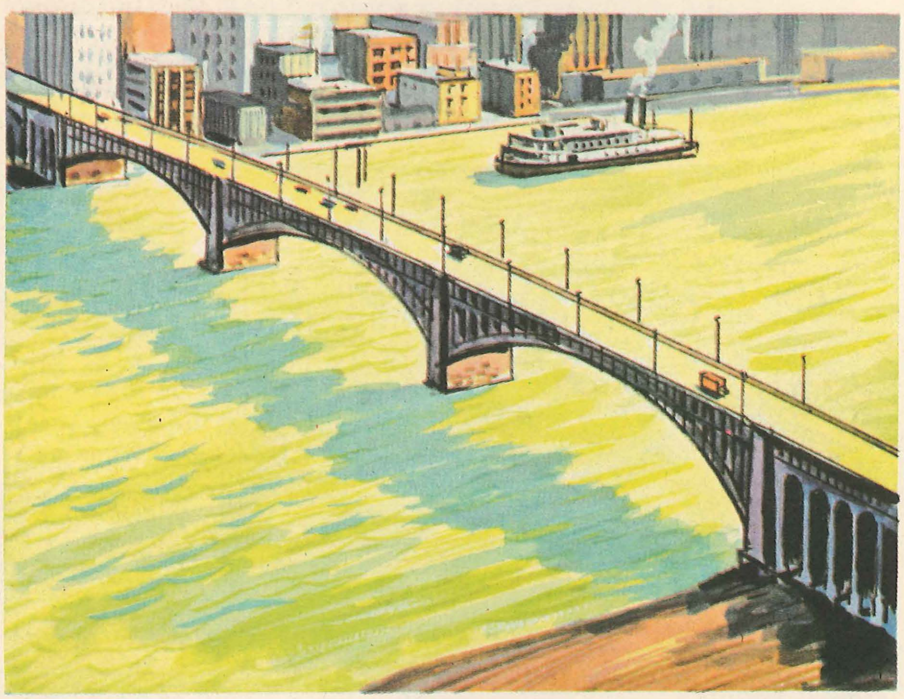


THE ROAD CAN HANG ON THE ARCH

Nature made this magnificent bridge in Utah. It spans Bridge Canyon, tributary from the south to Glen Canyon of the Colorado River.



Compare the size of the rider with the size of the gigantic arch.



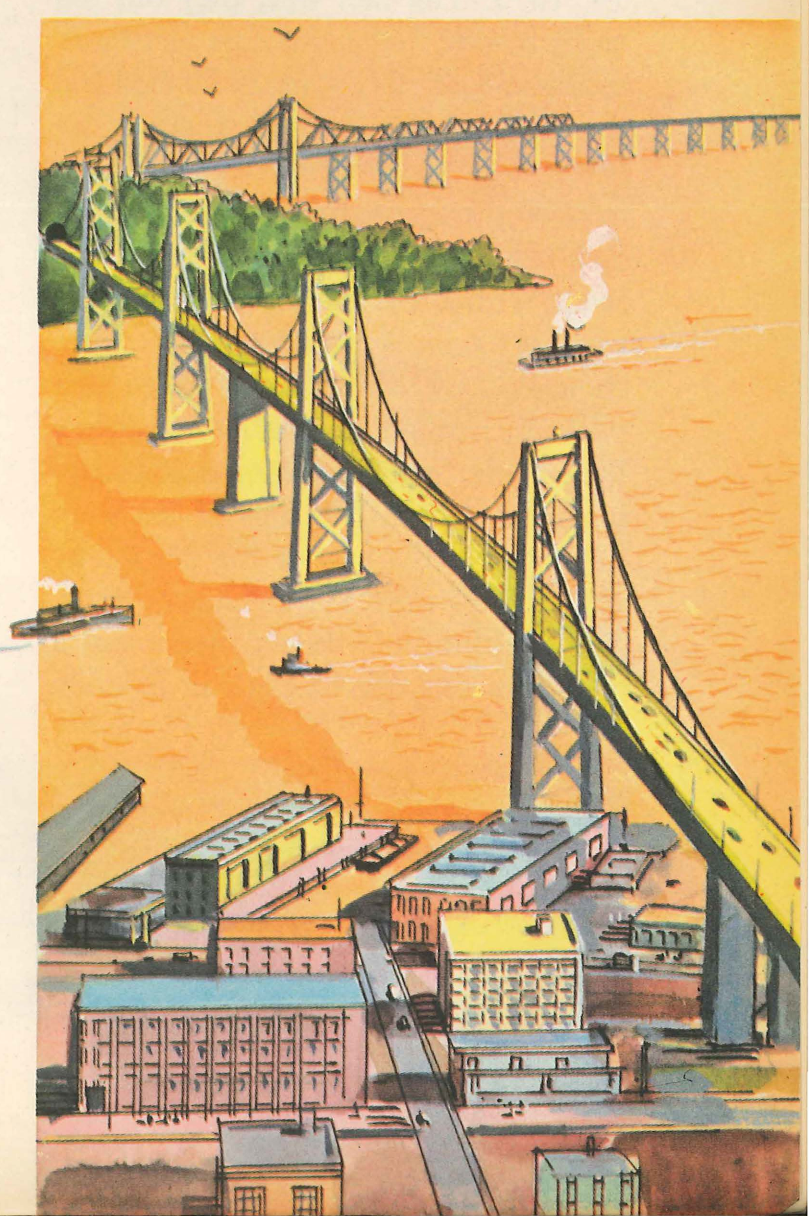
Eads' bridge across the Mississippi River.

The story of Eads' struggle to finish this magnificent structure is almost as dramatic as the story of the Roeblings. The Mississippi riverboat captains and the ferrymen tried hard to keep him from building it at all, and even when it was nearly completed, the U.S. Army Engineers suddenly ordered Eads to tear it down! But President Ulysses S. Grant knew Eads, who had built gunboats for

The beautiful Ponte Vecchio, the "Old Bridge," spans the Arno River in Florence, Italy. Not many bridges still stand which carry houses and shops. If you walk across it, you have the feeling of walking in a street.

him during the Civil War, and orders from the White House soon put a stop to that nonsense.

The bridge consists of a long double-deck roadway and railway held up from beneath by a row of true arches. This meant that Eads had to build two stone islands in the mud of the river-bottom amid the swift, treacherous currents. To do this, he designed the first caissons ever used in America, and young Washington Roebling rushed out from New York to watch and learn. Eads' caissons had to go even deeper than Roebling's, and sand-hog after sand-hog died of "the bends." Caissons were so new that no one knew anything about caisson disease. No one suspected that it was caused by bubbles of nitrogen that formed in the workmen's blood when they went from air under a pressure of 40 or 50 pounds per square inch to air at its ordinary outdoor pressure of 15 pounds per square inch. Eads



The San Francisco-Oakland Bridge is the world's longest bridge.

fixed up a boat as a floating hospital and put his own doctor, Dr. Jaminet, in charge. Dr. Jaminet himself went down to investigate, got the bends and was paralyzed for weeks. But from this he discovered how to prevent the disease by having the men go from the compressed air of the caisson into special chambers where the air pressure could be let out very slowly. His discovery came just too late to save Washington Roebling. While the first of the three arches was being built, Eads went to London, England. He desperately needed money to finish the work, and some English bankers promised to lend him half a million dollars, but only if the first arch was finished by September 19, 1873. The fact was, they did not really believe that a structure like Eads' could be built. The workers hurried and the sides of the arch grew closer together, but the last steel pieces that were to fit at the top were five-eighths of an inch too long! This was because metal swells a little when it is heated, and the weather was unusually warm. The engineers got fifteen tons of ice and packed it around the steel, but just then the weather got even warmer. On September 16, forty-five tons of ice were used, but at the end of the hot sunny day the ribs were 1⅛ inches too long. The next morning the engineers sent a desperate message to Eads in London over the new transatlantic telegraph cable. He cabled back telling them where to find some special members which he had built in case this happened. That night the special ribs were put in place, and the cablegram announcing the completion of the arch arrived in London just in time for Eads to get his loan and save his bridge.

What is a suspension span bridge?

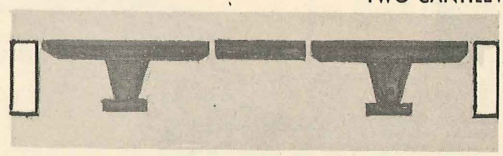
The third type of bridge is the *suspension span,* which is really a kind of upside-down arch. In the true arch, the compressive strength of the material carries the thrust around the curve to the riverbanks or *abutments.* In the suspension bridge, the tensile strength of the cable carries the pull of the load around the curve, over the towers and down to the abutments. The longest spans in the world are suspension bridges, but it takes tremendously good engineering to keep them steady. The Tacoma Narrows Bridge that fell in 1940 was a suspension bridge, but so is the span that replaced it ten years later.

How is a cantilever bridge built?

The fourth type of bridge is the *cantilever span.* A cantilever, as you would guess from its name, is a kind of lever like a see-saw. If you sit on one end of it, it

It is a far cry from the rope and plant fiber suspension bridges of the natives of the jungle to the Brooklyn Bridge, but the principle is the same.

The first great cantilever bridge was over the Firth of Forth in Scotland.



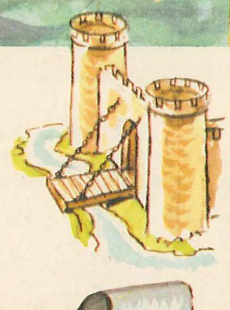
TWO CANTILEVER BEAMS WITH LIGHT-WEIGHT SUSPENDED SPAN IN BETWEEN

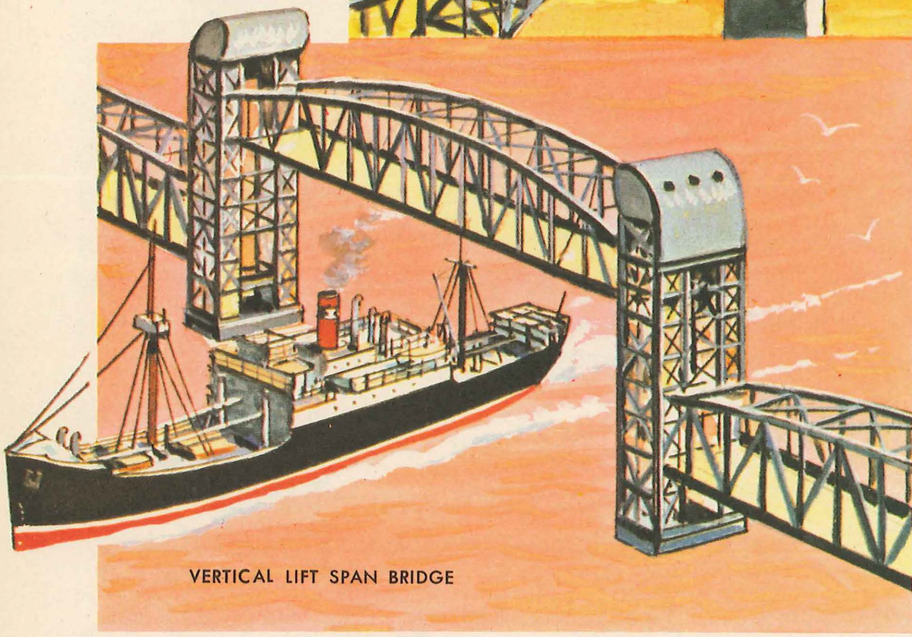
will hold up your weight as long as someone holds *down* the other end of it. A diving-board is also a cantilever. So is a dresser-drawer when you pull it part way out. The corbelled arch uses the cantilever principle. A cantilever span uses two simple cantilevers built end to end. First, two framework towers are built. Then, on each tower, a strong trussed cross-piece is built. Every time a length is added to one end of a cross-piece, the same amount is added to the other end, so the cross-piece is always evenly balanced and the tower does not topple. The two cross-pieces reach out nearer and nearer to each other across the river. When the ends over the water are only a short distance apart, the ends over the canal are anchored to sturdy piers, so the trusses cannot tilt. Finally a short truss called a *suspended span* is built between the near ends, joining them, and there is now a complete span between the piers. You can see the advantage of this kind of bridge; it is very steady. If you are walking on a railing, you hold your arms out like a cantilever to steady yourself. Most of the dead load is carried straight down the towers, because the main trusses are balanced on them. And it does not matter how deep or swift the river is, because the span can be built from the towers without ever going out in the water.

Where was the first cantilever bridge?

The first great cantilever bridge was begun in 1883, the year the Brooklyn Bridge was finished. There is a deep bay in the eastern coast of Scotland called the Firth of Forth, and here the fogs roll in from the North Sea and the gales shriek up from the lowlands and the waters pull swiftly and treacherously through the channel when the tide goes out. Two brilliant English engineers named Fowler and Baker planned a long railroad bridge across this Firth. A few years before, a new truss bridge 85 spans long had been built across the

Many bridges, like the drawbridges over the moats around a castle, were made movable for defensive purposes. In modern times, movable bridges are necessary to allow traffic on the water to pass where it would be impossible or too expensive to build bridges with sufficient clearance.





The most common movable bridges are the drawbridge (Bascule Bridge) with one or two movable leaves, the swing spans, in which a part of the bridge swivels 90 degrees, and the vertical lift spans, in which a span of the bridge moves vertically out of the way.

Firth of Tay to the north, and in a storm it had collapsed, carrying a trainload of people to their death in the waves. Fowler and Baker had studied this disaster, and had studied Eads' bridge at St. Louis and Roebling's in New York. They decided that only a heavy cantilever bridge would carry the fast Scottish express trains safely across the windy Firth. Their bridge used many ideas about caisson and steel work learned from the American engineers, but it was a strange structure, with three enormous cantilevers in a row, balanced on tiny stone piers. The Firth of Forth bridge, nearly 75 years old and still considered the finest of its kind in the world, is the only bridge anywhere over which trains are allowed to speed at 60 miles an hour.





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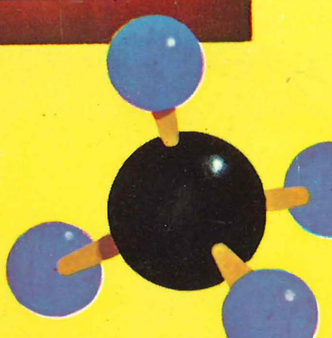


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